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Faulting and forced folding in the Rocky Mountains foreland

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ABSTRACT

The structural basement in the Rocky Mountains foreland deforms by faulting and rigid-body rotations. The faults at the interface between the sedimentary and crystalline rocks can be anything from low-angle reverse to normal faults. Despite the range of geometries, the total assemblage of faults and rotations is best explained by a movement system that is dominated by vertical motions along faults, many of which are curved in cross section. The first causes deep within the crust are not sufficiently well documented in the geophysical record to justify a firm interpretation. However, there are certain conditions recorded in the geologic history of the region and in the surface structures that place constraints even on speculations. With these constraints, vertical movements seem more likely to dominate than horizontal movements. The sedimentary layers are deformed primarily by forced folding. Their final geometry is a product of several parameters such as welding and stratigraphic make-up. Measurements on natural folds demand that the section either thinned or detached. Detachment without appreciable thinning further requires that (1) large displacements occur within the sedimentary section and (2) at the termination of these folds, the movement must be in several directions. Geologists' intuition as to how the layered rocks achieved their shapes is not always correct, but field data combined with experimental and theoretical data provide a basis for understanding these folds. It is concluded that the structural style in the Rocky Mountains foreland is not unique, but rather it is only an excellent example of a more universal class of deformation, namely, forced folding.

INTRODUCTION

The structures within the Rocky Mountains foreland have long attracted the attention of the geological fraternity. Well they should have because they are young enough to have many of their features preserved, they are well exposed both vertically and horizontally, they present perplexing problems to challenge the intellect, and they occur in magnificent terrains that excite geologists. The features have been mapped, modeled, drilled, theorized about, and shot seismically. They have created joyous careers for some and lifelong enemies and frustration for others. Therefore, to try to combine all of the science and emotion into one unprejudiced account would only be possible by a writer outside the geological fraternity. I am, thankfully, not outside of this fraternity, so my admission from the beginning is that I am writing from 20 years of active, but prejudiced, interest in the subject.

This paper will be based primarily on the work of the past 20 years, and there are two major objectives. The first is to describe the general tectonic class to which most of the structures in the Rocky Mountains foreland belong. The second is to review what is known about these structures and what can be concluded from them.

Prucha and others (1965) referred to the Rocky Mountains foreland as the Wyoming province because the styles of deformation in the entire region are so characteristic of the state of Wyoming with the exception of the western Wyoming thrust belt. In their use of "Wyoming province" they emphasized that the area characterized by this structural style extends far beyond the boundaries of Wyoming into parts of Montana, Colorado, Utah, New Mexico, and Arizona. That the layered rocks in this province are capable of considerable folding has been emphasized by Berg (1962), Prucha and others (1965), Stearns (1971), Stearns and others (1975), and Cook and Stearns (1975), to mention only a few. How the layered rocks fold, however, is a subject more debated. In this paper I will argue that within this region, the fold style is a manifestation of a universal tectonic type: forced folding.[1]

FORCED FOLDS

A forced fold is one in which the final overall shape and trend are dominated by the shape of some forcing member below. Imagine a series of wooden blocks of irregular size and shape on a table top; the blocks are covered by a layer of some pliable material, such as a rubber sheet. If the blocks were then differentially tilted and rotated and the sheet was forced to conform to the irregular surface, the resulting anticlines and synclines would be forced folds. This is opposed to end loading the rubber sheet where the size, shape, and location of the resulting folds would be controlled by the geometry and physical properties of the rubber sheet (free folds). That the fold style in the Wyoming province is primarily one of forced folding will be justified below, but some support for this idea already exists in the literature (Stearns, 1971; Stearns and others, 1975; Stearns and Weinberg, 1975). This fold style has also been correctly referred to as "drape folding," but a drape fold is only a specific type of the more general class.

In general, the forcing member for a forced fold can be anything from an intrusive sill (Johnson, 1970; Savage, 1974), to faulted basement (Stearns, 1971), to a faulted massive sedimentary unit such as the Ellenberger Dolomite in the Permian basin (Elam, 1969). Another way to describe a forced fold is to consider it as a fold type that allows rocks to go from a discrete discontinuity in the displacement field (fault) to a more widespread or integrated total displacement. In Figure 1a, the discrete discontinuity in the displacement field that is implied by the fault

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[1] The term "forced folding" was proposed, but not published, by the late George M. Sowers (personal commun. about 1971).

in line *AA′* at point *X* has been absorbed by the folded layer *BB′* and distributed over region *Y* as illustrated in Figure 1b.

Because forced folding is dependent on the shape of the forcing member, originally horizontal sedimentary layers ~~are generally~~ loaded at high angles to layering. When loaded at low angles to layering, free folding usually occurs even though in such a loading system, forced folds can develop as a secondary result.

The large strength anisotropy imparted to most sedimentary rocks because of their depositional layering is very important to the forced-folding process. In order to accomplish any folding, but especially forced folding, a great deal of internal slip (along bedding planes) is required. The cohesive strength across natural depositional layering is usually much less in sedimentary rocks than across any other original plane through the intact material (Donath, 1961). Bedding planes become prime candidates for slip planes because the shear stress needed to cause slip along them essentially must only exceed the coefficient of sliding friction. Furthermore, natural bedding enables slip to be distributed over large volumes of rocks in small increments without having to overcome the bulk cohesive strength for every new slip plane. On other planes, not only must the coefficient of friction be exceeded before sliding can occur, but the cohesive strength must be overcome as well.

The ease with which forced folding occurs and the specific geometries that result are the combined effect of several physical parameters, but none is probably more important than depth of burial during deformation. That is, the low cohesive strength due to bedding becomes less and less an advantage with increasing depth. As burial increases, the normal stresses across the flat-lying bedding planes increase (assuming normal pore pressure), and therefore, the amount of shear stress needed for slip along them correspondingly increases. In other words, in beds loaded at high angles to their layering, increasing burial tends to make faulting an easier mechanism of deformation than folding until ~~burial becomes so great that the~~ entire rock mass becomes ductile (metamorphism). It is likely that deeply buried sections (about 7,000 m deep) would fault and behave as part of the faulted forcing member provided that they remained brittle. The sharp discontinuity between faulting and folding illustrated in Figure 1 is only possible when dealing with a brittle and statistically homogeneous forcing member beneath a shallowly buried sequence of layered rocks. Such a system produces a lower region that is fault-dominated, (the lower forcing member) and a section above that is fold-dominated. If, however, the layered sequence is thick (in excess of 5,000 or 6,000 m), there very well may develop three distinct vertical zones in which different mechanisms predominate. In the forcing member, faulting is the dominant mechanism; in the very shallow layered rocks, folding is the dominant mechanism; but between areas of dominant faulting and dominant folding, there may be sequences in which mixed faulting and folding occur. One excellent exposure of this type of behavior crops out

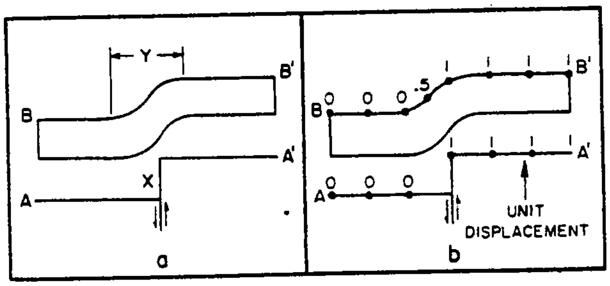

Figure 1. Schematic illustration of displacement in a forced fold compared to displacement in the faulted forcing member. The discontinuity in line *AA′* is spread out over region *Y* in the fold.

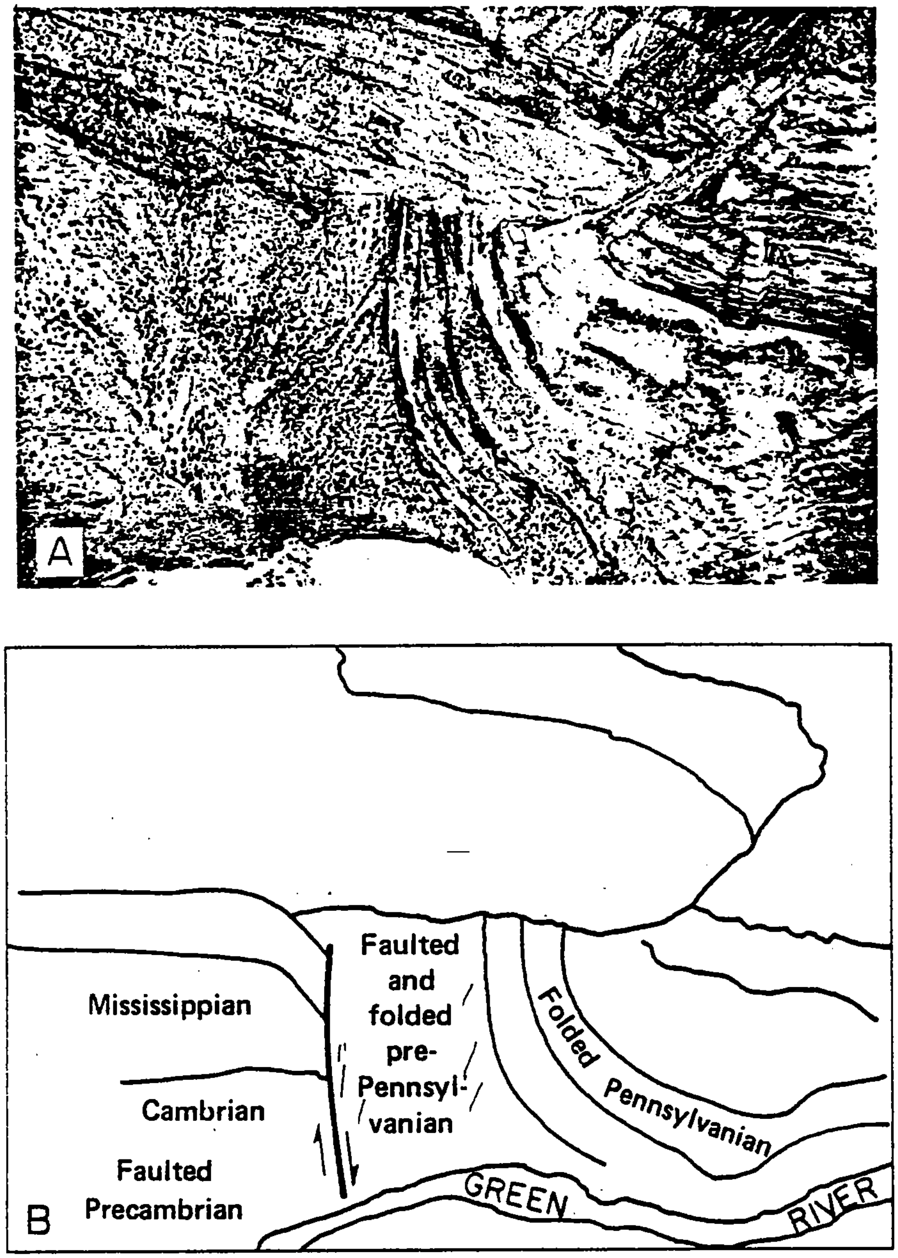

Figure 2. (A) Photograph of section of rock that is fault-dominated at the bottom and fold-dominated at the top but with mixed faulting and folding in the middle. (B) Tracing of photograph in Figure 2A; ages of rock units are shown.

along the Green River in the eastern Uinta Mountains and was mapped by Untermann and Untermann (1965). Here the layered rock sequence is thicker than 5,000 m, and the upper part of the Precambrian and the lower part of the Cambrian section are dominated by faulting (Fig. 2). The Upper Cambrian through Lower Pennsylvanian rocks are deformed by a combination of faulting and folding, but in the younger rocks, faulting is totally absent and folding is the dominant mechanism.

A second condition that greatly affects the style of forced folding is how strongly

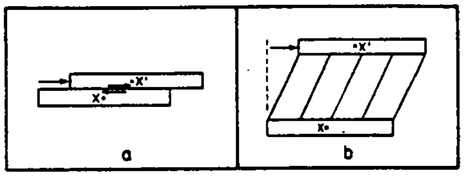

Figure 3. Schematic illustration of two types of offsets. (a) Slip of one rock layer past the one immediately below. (b) Slip of one layer relative to another below by flow within an intervening layer.

the layered sequence is welded to the forcing member. If the layered rocks are not easily decoupled from the forcing member, so that interstratal slip cannot become effective, the layered rocks tend to fault rather than develop folds. How strongly the layered rocks are welded to the forcing member can be a function of burial alone, because the higher the normal stress across the base of the layered sequence, the more difficult it is to decouple these rocks from the forcing member. However, burial is not the only condition that affects the welding. The ductility of the unit immediately above the forcing member also affects the degree of welding. At least two types of offset can occur (Figs. 3a and 3b). In the first case, slip occurs on a single plane within the layered rocks, and there is discrete separation between previously adjacent points. The physical parameters that affect such an offset, often called a detachment, are the normal stress across the plane and the coefficient of sliding friction between the materials of the two layers. (The cohesive strength across the contact is ignored here because it would only vary slightly with changes in rock type.) Considerable offset of one layer relative to another also can be accomplished across intervening thick ductile units without ever involving the frictional characteristics of discrete continuous planes (Fig. 3b). Separation of points X and X' is the same in each case, but in Figure 3b it has occurred owing to the ductility of the intervening unit. Because this is primarily a ductility control, it would be enhanced by higher confining pressures. The higher pressures, however, would make the mechanism illustrated in Figure 3a more difficult. Any weak, ductile stratigraphic unit is a good candidate for accomplishing the sort of offset illustrated in Figure 3b. Obvious examples are thick clay-shale or salt units. Field experience has shown that intuition is not always good in determining what rock types will allow offsetting in a section because of their ductility. For example, in the Freezeout Mountains, Precambrian granitic material serves as the forcing member. It is immediately overlain by a thin limestone (Mississippian) and a thick sequence of bedded sandstones and limestones of the Casper Formation (Pennsylvanian). Such a section might not seem to be ductile, but in this case the Pennsylvanian sandstones served as an excellent decoupling unit because of their ability to flow cataclastically. Here, owing to the bulk ductility of the sandstone, drape folds of at least 1,000-m (3,000-ft) displacement have formed without faulting of the sedimentary section.

Two other factors that affect the eventual geometries in forced folding are the physical make-up of the forcing member and that of the folded sequence. If the forcing member is, for example, shallowly buried granitic material. not only is faulting the dominant mechanism, but folding is completely excluded (for reasons, see Stearns, 1975). If the forcing member is a massive dolomite unit such as the Ellenberger Dolomite of West Texas, then because of both its brittleness and its lack of closely spaced bedding, faulting may still be the dominant mechanism. However, there may be small amounts of folding that accompany the faulting in the forcing member.

The make-up of the folded part of the system also has a great deal of control on the resulting geometry. If the stratigraphic layers above the forcing member have physical properties so that thinning occurs at lower stress differentials than are required for massive interstratal slip, the units fold over the forcing member, but are attenuated or thickened as is demanded by the kinematics of the fold. If the physical make-up of the layered rocks is such that interstratal slip occurs at lower stress differentials than does appreciable thinning, individual layers experience lateral mass transport into the fold, and little or no thinning accompanies the folding process. The tendency for any given stratigraphic sequence to behave according to either of the endpoints may be more a product of their bulk behavior than the individual characteristics of any specific layer (Stearns, 1969). Examples of thinned sections have been reported for Mesozoic sandstone and shale sequences at Casper Mountain, Wyoming (Vaugh, 1976), Hamilton dome, Wyoming (Berg, 1976), in Pennsylvanian sandstone sections in the eastern Uinta Mountains (Cook and Stearns, 1975), and in Triassic sandstone units in the Uncompahgre uplift (Stearns and Jamison, 1977). Examples of nonthinned sections have also been reported (Stearns, 1971; Stearns and others, 1975; Stearns and Stearns, this volume). It is important to note that although the end-product geometry is different for rocks that thin as opposed to those that simply translate without thinning, this is only a difference in mechanistic response within the layered rocks to the same causative loading conditions, not a difference in the fold type.

The final parameter that seemingly affects the behavior of the layered rocks is the angle at which the fault leaves the forcing member. Because forced folding (as defined in this paper) usually is produced by loads at high angles to the bedding, faults that leave the forcing member as high-angle reverse faults (60° or steeper) or as very high angle normal faults (75° or greater) are more effective in producing the folds. If the layered rocks in the immediate vicinity of the top of the forcing member are put into too much extension (normal faults that dip less than 75°), the layered sequences tend to fault rather than fold. Although precise numbers for the exact amount of extension that causes this phenomenon in natural situations are not available, the general principle is in accord with the laboratory findings of Heard (1960). He found that rocks are considerably more brittle in extension than when put into even slight compression. The requirement for compression, as opposed to extension, by high-angle reverse faulting should not, however, be confused with low-angle reverse faulting (overthrusting), which tends to produce faulting and/or free folding in the layered rocks. The precise dip angles for fault control from natural examples are not available, but it should be noted that there are no known examples of drape folds over proved normal faults that dip 60° or less. Drape folding can occur over very high angle normal faults. For example, the frontal normal fault at Rattlesnake Mountain in Wyoming dips about 85° where exposed, and there is considerable drape folding above this displacement (Stearns, 1971). In the Owl Creek Mountains, however, the Boyson fault leaves the basement as a 60°-dipping normal fault. Over this fault the same sequence of layered rocks, under essentially the same deformation conditions as existed at Rattlesnake Mountain, are faulted through with little or no folding (Fanshawe, 1939). If the fault leaves the basement at low angles (less than 45°) it also continues into the layered rocks (Stearns and others, 1975).

FORCED FOLDS IN THE ROCKY MOUNTAINS FORELAND

Statement of the Problem

Even casual study of such a simplified map as is shown in Figure 4 indicates several of the major tenants that must be included in a discussion of this region.

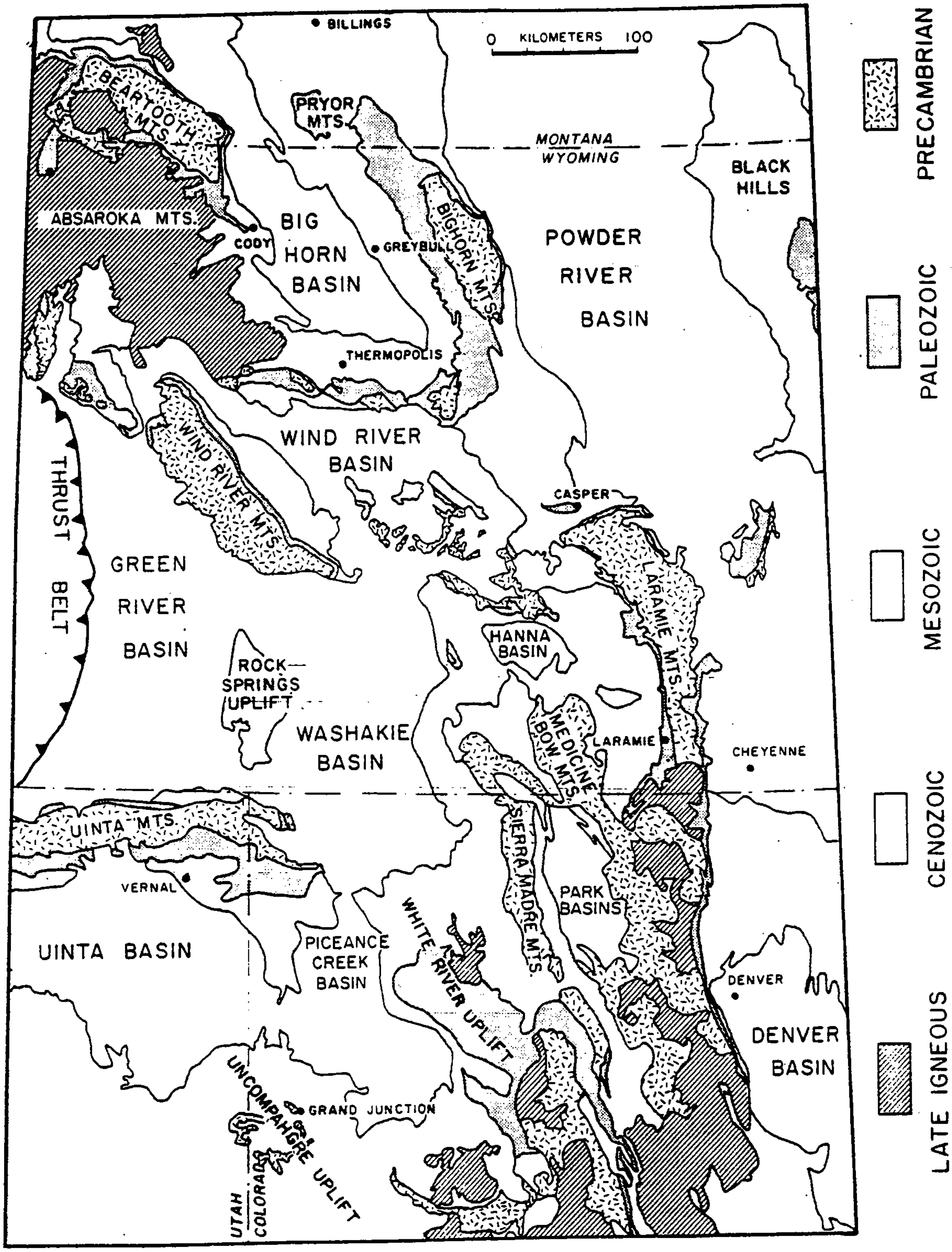

Figure 4. Generalized geologic map of part of the Rocky Mountains foreland.

Because most of the major mountain ranges are cored with Precambrian basement rock, it is evident that the basement is involved in the structural style. It is also evident that although there are statistically dominant trends to the structural features, the fabric of the structural trends is not as strong as it is in thrust belts. From the distribution of mountains, uplifts, and basins, it is apparent that whatever the deformation style, large-scale differential vertical movements occurred. The basins, like the mountains, have several different trends and shapes. Some of them are nearly oval (Bighorn Basin), others triangular (Wind River Basin), and others almost round (Hanna Basin).

There are several features concerning the overall style that are not observable from such a simplified map, but are definitely facts in the geologic record. Throughout the region, the Precambrian basement surface was peneplaned before the transgression of Cambrian seas. This peneplaned Precambrian surface is for the most part a crystalline basement in which planar anisotropies play a very small mechanical role. The two areas of exception are in and around the Uinta Mountains and in the southwestern corner of the Wind River Mountains, where the upper Precambrian section does contain rocks with sufficient layering to impart a strength anisotropy. This peneplaned surface was deformed during the Laramide orogeny by a series of rigid-body rotations that resulted in absolute upward and absolute downward motions of the original planar surface. The peneplaned surface at the beginning of the Laramide orogeny, as attested to by sedimentary thicknesses, was a relatively flat-lying surface except in the westernmost sections of Wyoming. This surface at the beginning of deformation was between 3,000 and 3,500 m (10,000 and 12,000 ft) below sea level. Today, mountain peaks with eroded Precambrian rocks range up to 4,800 m (15,500 ft) above sea level, and the original planar Precambrian surface in the deeper parts of basins is between 9,000 and 9,500 m (30,000 and 40,000 ft) below sea level. Most of the basins are strongly asymmetric. Most of the mountain blocks are rotated so that dips on the previously horizontal Precambrian surface range between 10° and 16°. However, a few of the mountain blocks, notably the Uncompahgre uplift and the Beartooth Mountains, are plateau-type uplifts where the elevated Precambrian surface is nearly horizontal. Some of the rotated blocks are rotated toward, and some away from, an adjoining basin. Some basin edges are formed by a single, uniformly rotated mountain block (for example, the south side of the Wind River Basin, which is formed by the north flank of the Wind River Mountains). Other basin edges, such as the eastern flank of the Bighorn Basin, are formed by separate blocks rotated in different directions. Along the northeastern flank of the Bighorn Basin, the mountain blocks are rotated away from the Bighorn Basin and toward the Powder River Basin; in the southern part of the Bighorn Basin, however, the mountain blocks are rotated toward the Bighorn Basin and away from the Powder River Basin. One final observational fact is that within Wyoming, some mountain blocks are bounded by faults that are very high angle, whereas other mountain blocks are bounded by much lower angle reverse faults. In general there are more high-angle major faults in the northern part of Wyoming and more low-angle major faults in the southern part. It is not impossible to find a low-angle fault feature in the northern part of the province, nor is it impossible to find a high-angle fault feature in the southern part of the province; however, the occurrence of high-angle faults is more common in the north than in the south.

These observations are neither profound nor new, but they all must be included in any attempt at explaining the structural style in a general way. They cannot be taken one at a time, or conveniently ignored. If a system is going to explain the structural behavior of this region, it must be able to account for all of these facts within the framework of the explanation offered.

The structural style under consideration has been variously categorized in the geologic literature as reviewed by Berg (1962). Terms such as "block faulting" or "Rocky Mountains foreland faulting" have been applied. These descriptive terms serve well to designate the geographic area or to characterize the particular geometric form. However, they do little to specify the actual structural problem under attack. To specify properly the structural problem of the region it should be stated both mechanically and geologically. In the most general mechanical terms the problem is that of the large-scale behavior of layered, inhomogeneous, anisotropic sequences of varied lithic type (sedimentary rocks) as they are deformed over rotated blocks of shallowly buried, statistically isotropic, homogeneous, continuous basement. The geologic problem is that of the response of layered sedimentary rocks as they are deformed over blocks of Precambrian crystalline basement that are bounded by faults with various dip angles. Stearns and others (1975) argued that if the faults are high angle (from 75° normal to 60° reverse), the layered sequences in the Rocky Mountains foreland are folded over the tops of the basement blocks (forced folding). Both the mechanical and the geologic statements of the problem emphasize the behavior of the forcing member and the behavior of folded layered rocks. It is only when the layered rocks are faulted through that there is any remote continuity of structural styles between the basement and the overlying sedimentary veneer. For these reasons, then, the response of the basement will be considered separately from the response of the overlying sedimentary rocks. In some cases, the two responses will be similar, but in most, they will be distinctly different.

Structural Response of the Basement

The term "basement" as used here has only a mechanical connotation. In the Rocky Mountains foreland the basement is all of Precambrian age, but this is only an accident of the particular rocks that occur within the region, and there is no necessity to place an age restriction on the structural basement. The upper surface of any structural basement should be that level below which there is no reasonable expectation of the occurrence of significant mechanical layering. The basement is, therefore, that mass of rock which is statistically homogeneous, isotropic, and continuous. Throughout the foreland the basement is what the field geologist would refer to casually as Precambrian "granite." Although in detail the rock is not always mineralogically a granite, it is a crystalline material in which layering plays no role. Precambrian rocks having either sedimentary layering or closely spaced metamorphic foliation should not be considered basement. Regions in the foreland where Precambrian rocks with such layering occur are the extreme southern end of the Wind River Mountains, the southern Front Range below the Canon City embayment, and the Uinta Mountains.

The material properties of the basement in the foreland are such that the rock behaves brittlely up to the point of rupture unless it is subjected to very high confining pressures and/or temperatures (Moho conditions or very near intrusions). Certainly the burial conditions during Laramide deformation in the Rocky Mountains foreland (less than 4,500 m) require that the upper several thousand metres of basement behave as a brittle material. This fact, which is so clearly demonstrated in the laboratory (Borg and Handin, 1966), has not been easily accepted by many geologists, who still insist upon significant folding of the basement. If one accepts that during Laramide deformation, for some reason unknown to physics, these basement rocks changed their mechanical properties and folded, one must also accept an extremely coincident event of post-Laramide erosion—that is, the contact between Precambrian granite and Cambrian sedimentary rocks is nowhere significantly arched or folded, although this contact is well exposed in the Wind River, Big Horn, Owl Creek, and Gros Ventre Mountains as well as over vast regions in the Uncompahgre Plateau. The contact certainly is rotated, but the dips in the rotated blocks are uniform and arching is absent. Folding of the basement has been *interpreted* by connecting two linear rotations in opposite directions with a curved surface, or else strictly by interpretation of nonexposed basement. If the basement is truly folded on a significant scale, nowhere is this folding exposed for direct observation. As will be discussed below, at the sharp edges and especially corners of brittle basement blocks, there can be a certain amount of closely spaced breakage of the brittle block that results in a small, highly broken, curved contact, but this behavior is on a scale that is trivial relative to the total deformation. With regard to this problem of folded basement, considerable attention has been drawn to a small fold at the Cambrian-Precambrian contact above Manitou Springs, Colorado. (This outcrop has since been removed during highway construction.) Even though the fold was less than 30 m (100 ft) in amplitude, it had been used as a demonstration of folded basement. However, both Hudson (1955) and Stearns (1971) showed that the upper Precambrian surface is weathered into a gravel, and it is this material that is folded with the Cambrian rocks. In this locality, continuous basement only exists below the weathered zone in the Precambrian rock. For all of these reasons, then, it will be assumed for the remainder of this paper that the basement, as defined here, did not fold significantly under the physical environment to which it was subjected during Laramide deformation.

The basement does fault, and it faults by a myriad of different fault types and inclinations. As Wisser (1957) pointed out, major mountain blocks in the Rocky Mountains foreland are bounded by virtually every type of fault that is geometrically classified. Prucha and others (1965) argued that many of the geometries they observed were best rationalized by a fault that was curved and steepened with depth (upthrust fault). I have argued that in order to avoid volume problems, all major faults in the basement (with the exception of certain normal faults) must be curved (Stearns, 1975). It is, therefore, a matter of direct observation that many different fault types coexist in the foreland, and from the material properties of the basement, it is a requirement that these faults, at least in the upper several thousand metres of the basement, must be curved in order to produce the observed rotations without deforming the basement beyond its ductile limits.

What is not agreed upon is the general tectonic system that produced these faults. Are they produced solely by (1) horizontal compression involving large-scale underthrusting or overthrusting of the basement, or are they produced primarily by (2) differential vertical movements without large-scale overthrusting or underthrusting. Deep geophysical properties of the Earth and crust-mantle relations are not sufficiently well understood in the foreland to conclusively answer these questions, so the arguments persist. There are, however, certain geologic arguments that can be presented for or against either case. They are based upon surface considerations and cannot be used conclusively, but at present they form the only basis for decision. Each of the two above-listed possibilities will be taken up separately.

Arguments Concerning Horizontal Motions

There are two principle reasons that make large-scale horizontal motions in the basement of the Rocky Mountains foreland an appealing movement scheme. The

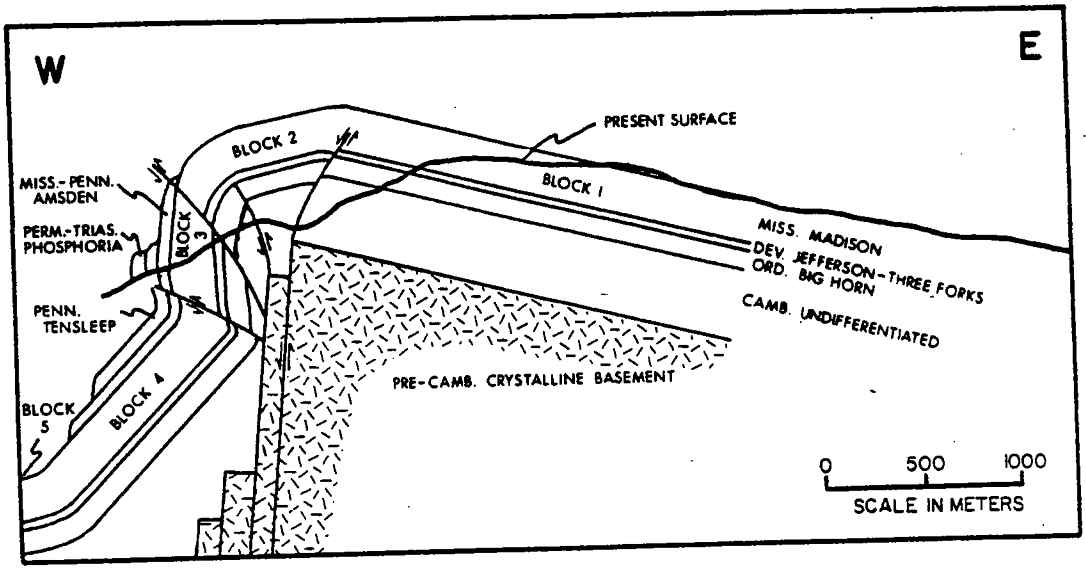

Figure 5. Cross section of Rattlesnake Mountain west of Cody, Wyoming. Block designations after Stearns (1971).

first stems directly from the observation that there are areas in the province where the basement rides out and over the sedimentary veneer along low-angle fault zones. Examples of this are particularly well displayed along the southwestern front of the Wind River Mountains. Seismic studies and drilling have established that such features also exist along the southern boundary of the Owl Creek Mountains and along the southwestern front of the Granite Mountains. There are other regions, such as along the front of the Beartooth Mountains and the north and south flank of the Uinta Mountains, in which sedimentary rocks are repeated across low-angle faults that must be associated with the basement deformation. The second reason is that with large-scale horizontal motions, certain folding problems in the overlying sedimentary layers are more easily rationalized. That is, superincumbent folding in the layered rocks would be more easily explained if the basement had moved horizontally. I have pointed out (Stearns, 1971) that many of the layered rocks in the Wyoming province form drape folds which are accompanied by little or no thinning of the Paleozoic carbonate sections. Rattlesnake Mountain is one of these structures (Fig. 5). If only this cross section is considered, it is much easier to explain the combination of continuous folding and nonthinning by shortening the basement. There are, however, several observations that make large-scale horizontal motions in the basement less appealing, and furthermore, neither of the reasons that make horizontal motions attractive is incompatible with differential vertical uplift. If the long, rotated blocks, such as the dip slope of the Wind River Mountains into the Wind River Basin, are assumed to be underlain by low-angle thrust faults, a series of geometric near-impossibilities arise. These geometric difficulties do not manifest themselves when only two-dimensional cross sections are considered. However, if broader regions and three dimensions are considered at the same time as cross sections, then horizontal motions become less appealing. For example, Figure 6 is a simplified map of the mountains and basins that appear in Figure 4 with the movement directions that are necessary if each of the major mountain blocks is underlain by an overthrust (solid arrows) or an underthrust (open arrows). Each of the solid arrows is drawn assuming that major basement

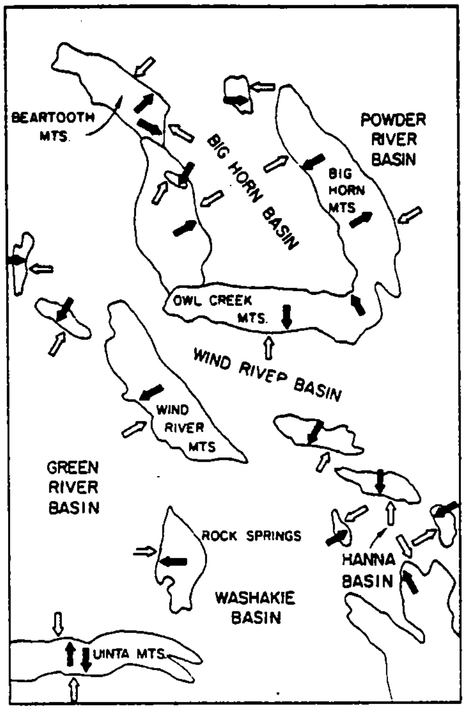

Figure 6. Generalized map of mountains and basins showing movement pattern required for underthrusting (open arrows) and overthrusting (solid arrows).

blocks (like those shown in Fig. 5) are underlain by a fault that flattens with depth ("sled runner") and that the upper plate is the active-movement plate. The open arrows are drawn as if each of the major basement blocks are underlain by a shallow-dipping fault in which the basinward block moves underneath an uplifted mountain block. Figure 6 indicates that although single cross sections through any of the blocks may appeal to low-angle horizontal motions, when the entire region is considered, the horizontal motions must have been in many different directions. Multiple sources, one for each horizontal motion, then need to be found. It is difficult, if not impossible, to imagine a driving system that would produce horizontal motions in so many different directions. Even this is not the most damaging argument to such a scheme. The patterns shown in Figure 6 are even more paradoxical when the behavior of the upper basement surface in the Rocky Mountains foreland is considered. This behavior pattern is one of rupture and rigid-body rotation. Consider, for example, the difficulty in explaining the near-perpendicular horizontal movements that would be required in the Beartooth Mountains. Such motions in brittle materials would produce unacceptable volume discrepancies that would seemingly result in large holes in the basement. The problem in and around the Beartooth Mountains (Fig. 6) is expressed again and again within the foreland. For example, in the north end of the Bighorn Basin, if underthrusting is accepted, it is necessary to underthrust in two directions away from the center of the basin. The Big Horn Mountains present a different, but equally perplexing problem. The major blocks north of Greybull, Wyoming, are tilted toward the Powder River Basin—which would indicate that the northern part of the mountain range moved to the southwest if we invoke low-angle faults. The block south of Greybull, Wyoming, is tilted toward the Bighorn Basin; this would imply a large-scale horizontal motion to the northeast. Again, this seemingly leads to an uncompensated-volume system. Small basins such as the Hanna Basin present even more complexing problems. The Hanna Basin is about 30 to 40 km (20 to 25 mi) across, and yet it is 9 km (30,000 ft) deep. If horizontal motions are accepted as the dominant pattern of basement movement (either overthrusting or underthrusting) in the Hanna Basin, again an extreme paradox results. Underthrusting would produce a large void in the basement in the center of the basin, and overthrusting would require a system that can drive thrusts in an almost circular pattern. The large change in the horizontal-motion direction between the Wind River Mountains and the Owl Creek Mountains that flank the Wind River Basin would be equally difficult to explain. Between the Gros Ventre Mountains and Teton Mountains, a severe movement shift would be required. Likewise, the Green River Basin presents a problem to accepting this movement pattern. If the Wyoming thrust belt is due to underthrusting (as suggested by Royse and others, 1975) and the Wind River Mountains are also underthrust, again there is a severe volume problem in the middle of the Green River Basin. To explain the Uinta Mountains with overthrusting (black arrows in Fig. 6) is virtually an impossibility. Underthrusting in this case, for just the single mountain range, is a more acceptable movement scheme, but the underthrusting that would be required on the north flank of the Uinta Mountains is somewhat in conflict with the underthrusting that would be required for the Rock Springs uplift or the Wind River Mountains.

Another reason for doubting large-scale horizontal motions in the upper several thousand metres of basement in the Rocky Mountain foreland arises from examining the corners of basement blocks in three dimensions as opposed to concentrating on two-dimensional cross sections near the middle of the blocks. The geometry near the termination of a block, if horizontal motions in the basement were responsible for the observed structures, is illustrated in Figures 7a through 7d. Figure 7a is a schematic drawing of a rotated basement block relative to a horizontal plane where the arrows indicate the required motions of the block, if the fault flattens with depth as indicated by the dashed line. Figure 7b is a map view of the resulting Precambrian surface. Figure 7c illustrates what would be expected in the overlying sedimentary rocks if the motions in Figure 7a were correct. Arrow 1 across the front of the block in Figure 7c represents a simple fold. At the termination of the block, wrench motion is necessary; arrow 2 in Figure 7c schematically illustrates what the required motions would be. Figure 7d is a map projection of Figure 7c. The configurations represented in Figures 7c and 7d simply are not seen at the terminations of any of the blocks in the Wyoming province. Rather, Figures 7e and 7f illustrate reality. Over the uplifted and rotated blocks, the sedimentary veneer continuously drapes in two directions as illustrated by arrows 1, 2, and 3 in Figure 7e. The fold dies out along the end of the block as illustrated by arrows 2 and 3, and the map pattern illustrated in Figure 7f is the resulting fold configuration in layered sedimentary rocks. Figure 8 is a photograph at the end of Rattlesnake Mountain in a position that is approximated by arrow 2 in Figure 7e. It can be seen in the photograph of Figure 8 that the sedimentary units drape continuously over the end of the block, the fold dies out toward the right-hand side of the photograph, and there is no indication of any lateral motion on the end of the blocks. Rattlesnake Mountain is not a singular example of this occurrence. Areas in which I have observed behavior similar to that illustrated in Figure 7f are Rattlesnake Mountain, southeastern corner of the Beartooth Mountains, the Prior Mountains, numerous occurrences north of the Five Springs area in the Big Horn Mountains, the Elk basin structure, the Dry Fork Ridge structure in the northeastern Big Horn Mountains, the front of the Big Horn Mountains north of Greybull, structures in and around and including Circle Ridge anticline in the western Owl Creek Mountains, the northern Tetons, the central and southern Gros

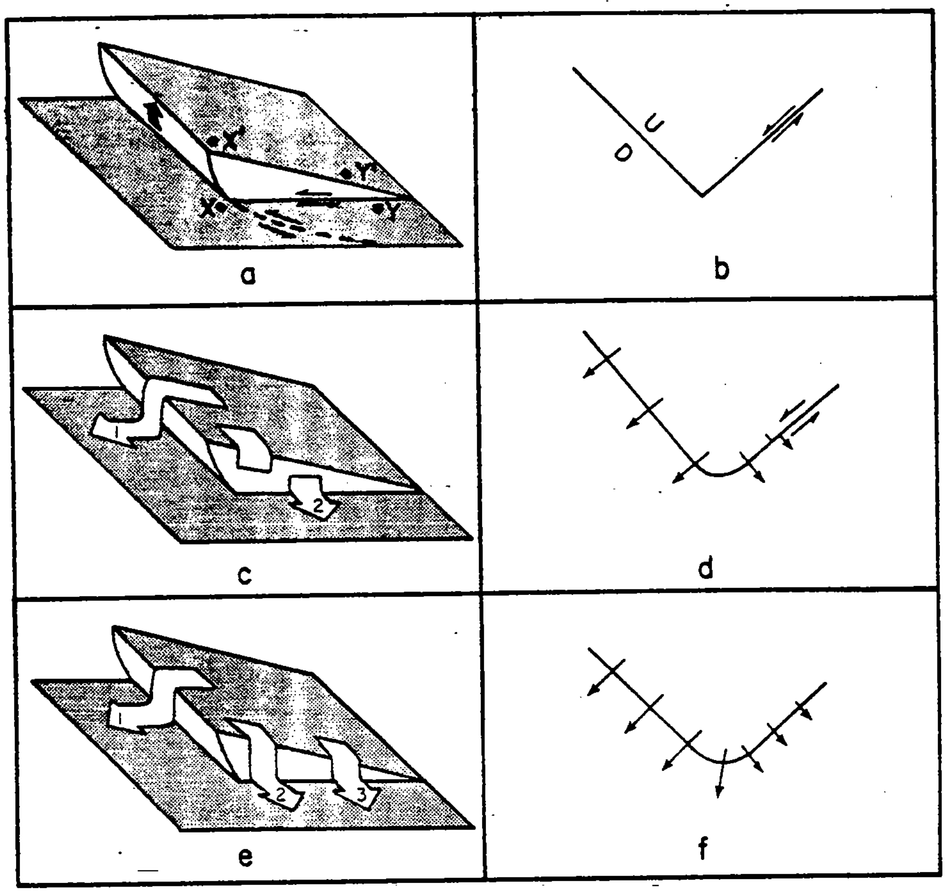

Figure 7. Schematic diagrams showing block configurations if they are underlain by a low-angle thrust fault (7a–7d) opposed to what actually occurs (7e and 7f); 7b, 7d, and 7f are simplified maps of the block configurations shown in 7a, 7c, and 7e, respectively.

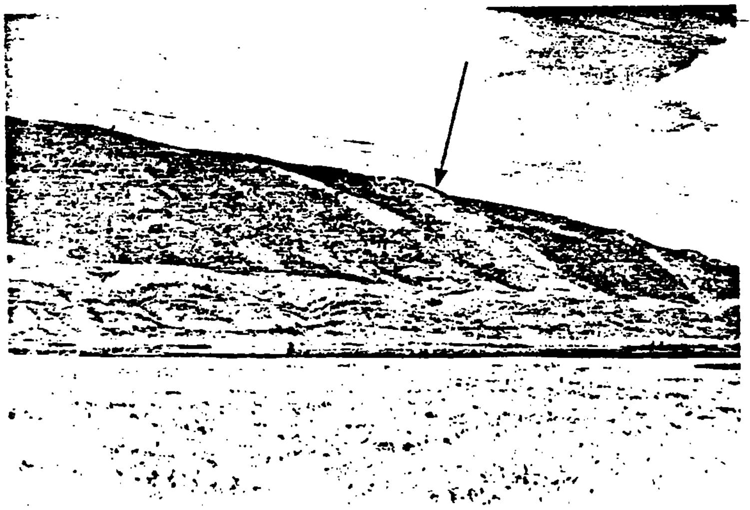

Figure 8. Photograph of the southeastern end of the Rattlesnake Mountain block showing continuous forced folds with no lateral offset. Continuity of fold over end of block can be seen on the steep hillside (at arrow).

Ventre Mountains, Casper Mountain, Seminoe Mountains, the Freezeout Mountains, Elk Mountain in the northern Medicine Bow Mountains, several places in the Front Range between Fort Collins and Denver, the eastern Uinta Mountains, and several places along the northeastern front of the Uncompaghre uplift. These occurrences, coupled with the fact that no place in the entire Rocky Mountains foreland have I ever seen a wrench fault large enough to accommodate implied horizontal motion, leads me to believe that the patterns illustrated in Figures 7e and 7f are the common behavioral patterns for the area and must be considered in any explanation of the region.

A third observational fact that casts doubt on large-scale horizontal motions is the plateau uplifts that occur within the Rocky Mountains foreland. Although the usual style is one in which the basement block is uplifted and rotated, there are areas in which the uplift results in nearly flat-topped blocks such as the Beartooth Mountains (Foose and others, 1961), the Cottonwood Canyon region in the northern Big Horn Mountains (Stearns and Stearns, this volume), and the Uncompahgre uplift (Lowman, 1963; Stearns, 1971). A rotated basement block such as that illustrated in Figure 5 could at least be geometrically produced by low-angle overthrust or underthrust faults in the basement. However, a large flat-topped block bounded on several sides by steep faults such as the Beartooth Mountains would be exceedingly difficult to produce by horizontal motions on low-dipping fault planes.

For all of these reasons it is difficult to accept horizontal motions on low-dipping planes in the upper several thousand metres in the basement. That is not to say that motions in the deep crust or upper mantle may not contain a horizontal component, but for that portion of the basement, at least the upper 6,000 m (20,000 ft), where brittle behavior must dominate, the observable geometries are difficult to rationalize with large-scale horizontal motions. If, however, large horizontal motions are interpreted, they must apply to all of the regional observations together, not just single cross sections through the centers of large blocks.

Arguments Concerning Vertical Movements

The opposite extreme of large-scale horizontal motions in the basement is a scheme in which most of the movements are vertical. Is there evidence that such motions have occurred within the Rocky Mountains foreland? As stated above, the peneplaned Precambrian surface at the beginning of Laramide deformation was approximately 3,000 to 3,500 m (10,000 to 12,000 ft) below sea level. Examination of the map in Figure 4 shows that Laramide deformation resulted in uplifted mountain blocks and downdropped basin blocks. Because the Precambrian surface in all of the basins is now much lower than 3,500 m (12,000 ft) below sea level and in all of the mountains it is considerably higher than that elevation, the inescapable conclusion is that the deformation produced large absolute up and absolute down vertical motions. Furthermore, the different trends of mountain systems and basins within the same general region would be allowed by vertical motions, whereas horizontal motions would normally result in uniform trends (Fig. 6). A pattern of vertical movement in the western North American continent is not unique to Laramide deformation. The evidence for this statement arises from what geologists know best of all: the stratigraphy of the layered Phanerozoic rocks. From Cambrian through Mississippian time, the western part of the continent underwent a long-wavelength, high-amplitude, low-average-displacement rate, differential vertical movement. Such a motion is verified by simple observation of the stratigraphy. Less than 1,500 m (5,000 ft) of Cambrian through Mississippian rocks in eastern Colorado are represented by more than 21,000 m (70,000 ft) of rocks of the same age in California (Gilluly, 1963). During Cambrian time there was transgression of the western continent (Haun and Kent, 1965) that moved from west to east and placed all of the upper Precambrian surface from California to Colorado at sea level (beach deposits) at some time during the Cambrian (Haun and Kent, 1965). By the end of Mississippian time, less than 1,500 m of rock had accumulated in western Colorado, but in excess of 21,000 m of rock had accumulated during the same period in California; this implies differential vertical motion of at least 19,500 m (65,000 ft) across the continent. Furthermore, this long-wavelength, high-amplitude, slow movement was relatively uniform along strike for thousands of kilometres. There is ample stratigraphic evidence to support the idea that the region from eastern Colorado to eastern Nevada was subjected to shorter-wavelength, intermediate-amplitude, rapid differential vertical motions during Pennsylvanian time. Source areas such as the Ancestral Rockies and Uncompahgre uplift became emergent and were not completely covered again until Cretaceous time. Other source areas such as the Emery arch probably remained subaqueous. Many basins were downdropped and became local depositional areas. Examples are the Bird Springs basin of southern Nevada, the Oquirrh basin in Utah, the Paradox basin in Utah and Colorado, the Maroon basin in Colorado, and the depositional area mostly in Wyoming that received the sediments that compose the Weber, Casper, and Tensleep Formations, all of Pennsylvanian age. Unlike the earlier downwarping that was continuous all along the western part of the continent, the Pennsylvanian motions produced a series of local source areas and depositional centers that in a sense fragmented the earlier more orderly system. Some of these Pennsylvanian differential vertical movements occurred over very short lateral distances. The zero isopach for the Cutler Formation (Pennsylvanian and Permian) on the northeastern side of the Paradox basin is only 8 km (5 mi) away from a section of rock 4,900 m (16,000 ft) thick. Most of the lower part of this formation is a sequence of coarse conglomeratic alluvial fans coming off from the newly created faulted front of the Uncompahgre uplift. Not until Cretaceous time were the irregularities caused by the Pennsylvanian differential vertical motions even approximately smoothed out. During Cretaceous time the western part of the continent again experienced a long-wavelength, relatively high-amplitude, slow differential vertical motion. Cretaceous stratigraphy clearly reveals that the central part of the area became emergent at least by Early Cretaceous time, and two troughs formed on either side of the uplift (Gilluly, 1963). The eastern downwarp, the Rocky Mountains trough, by the end of Cretaceous time was sufficiently depressed to accumulate in excess of 6,000 m (20,000 ft) of marine sediments (Haun and Kent, 1965). The exact elevation of the positive area is not known, but even the fact that it was emergent coupled with the depth of the adjoining trough indicates the magnitude of the differential vertical motions. Furthermore, these motions were very regular because all of the basin fill is shallow-water sediment. Finally, beginning in Paleocene time the eastern part of this area once again underwent a series of short-wavelength, intermediate-amplitude, differential vertical motions that produced the Rocky Mountains foreland, complete with its mountains and intermountain basins.

The cumulative post-Cambrian stratigraphy, therefore, demonstrates that the western part of the continent has long been subjected to differential vertical motions. There is at least a hint of cyclicity to these motions that begin with long-wavelength, widespread, slow movements and culminate in short-wavelength, irregular, rapid movements. The evidence for these movements comes from stratigraphy. This evidence, however, does not speak to the cause, but only to the result. Anyone attempting to explain causes must incorporate all of the stratigraphic information and not use just preselected parts of the total.

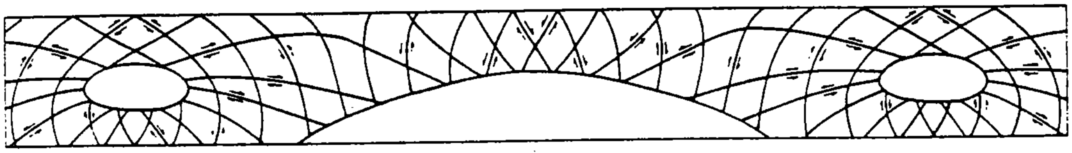

Figure 9. Diagram of potential faults that would be produced in a continuous, elastic block by differential vertical loads at the bottom (after Hafner, 1951). The lower boundary loads are in the form of a smooth sinusoid, the end loads are linear increases in the horizontal component of stress (normal burial), and the upper boundary represents the air-rock interface. Arrows indicate sense of shear on potential faults.

There are certain theories of deformation that help to explain the vertical movements during just the Laramide orogeny. Hafner (1951) dealt with the potential fault planes that might form in a homogeneous, isotropic, continuous, elastic segment of the Earth's crust due to differential vertical motions at the base of the unit. Hafner's paper not only addressed potential fault patterns in differential vertical uplift, but it is a hallmark paper in the geologic understanding of faulting in general. Up until 1951, and unfortunately for many years after, the geological fraternity tended to think of areas as if each were dominated by a single fault type—such as areas of normal faulting or areas of thrust faulting. Hafner's most important contribution was showing that from geologically realistic boundary conditions, a multiplicity of fault types can form as a result of a single loading condition in one area. His assumptions for material behavior were that the body is homogeneous, continuous, and isotropic and that it will behave up to the point of rupture as a linearly elastic body. These assumptions may not apply to all rocks, such as layered rocks of varying ductility or rocks near the base of the crust or the upper mantle. However, the material assumptions are not in contradiction to either field-observed or laboratory-measured behavioral characteristics of the upper several thousand metres of Precambrian crystalline basement in the Rocky Mountains foreland. Hafner's solution is a static solution that automatically limits its applicability to the formation of the potential shear fractures along which later displacement can occur. It does not address itself to large displacements that occur after the shear fractures form. His two-dimensional solution restricts any application to the centers of uniform regions that are long with respect to their width. This assumption, plane strain, could be applicable through the centers of basins or long mountain blocks, but definitely could not be applied near the terminations of blocks nor the ends of the basins. Figure 9 illustrates the solution to one set of boundary values that Hafner solved. In reality this solution is that of a thick beam bend occurring in elastic materials. In nonmathematical terms, it states that bending moments due to the uplift and downdrop at the base of the block must be added to standard-state conditions due to burial in order to produce the true stress field in the block. Because the beam is so thick, stress differences away from the center due to bending become large enough to cause rupture in rock materials (such as granite) before any observable deflection occurs at the upper surface.

There is only one way to test any theory that is based on so many assumptions. That way is simply to test a fit between what the theory predicts and what reality has shown. I have attempted to fit breaks predicted by Hafner to a region of the crust across the northern Bighorn Basin (Stearns, 1975). The apparent fit between the reality of this region and the theory was remarkably good, if the complexities of the real problem are considered. Through application of the Hafner shear fracture trajectories (potential faults), I was able to match the following features: (1) proper amounts of rotation for large basement blocks, (2) parallel or opposing rotations

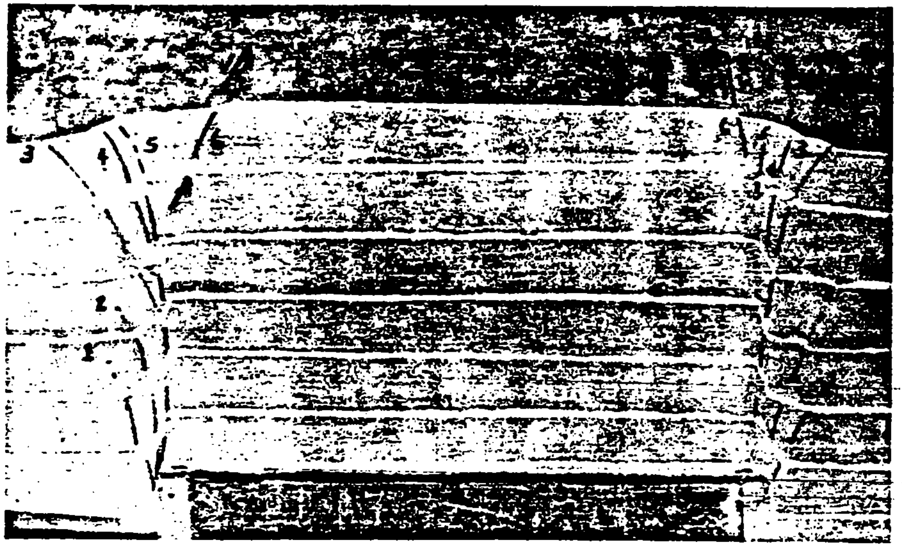

Figure 10. Photograph of the front view of a sandbox experiment. The lower piston has been displaced about 3 cm. Faults are traced on front; numbers refer to the order of their formation.

in adjoining blocks, (3) the proper position for known large-scale faults across the basin, and (4) the proper amount of throw on these faults. Furthermore, the composite movement on all of the faults selected from the Hafner diagram produced a basement configuration that would allow an asymmetrical basin the size and shape of the Bighorn Basin to form, and most importantly, this could be achieved without either creating space problems in the basement or violating the tenants of brittle behavior and rigid-body rotations for basement materials.

I concluded that not all of ~~the problems of basement deformation in the~~ Bighorn Basin could be solved by the theory of linear elasticity (Stearns, 1975). On the other hand, the remarkable agreement between the predictions of theory and the observations of the major structures in the northern Bighorn Basin cannot be ignored. I therefore concluded that "the correlation between prediction and observation is good enough for acceptance of the theory as the basis of the genesis of these regional structures. Furthermore, the geometrical relations of this area are explained by faults that are mechanically compatible."

Sanford (1959) did a study similar to that of Hafner. The major difference between the two studies, with the exception of techniques involving displacement rather than stress analysis, occurs in the lower boundary condition. Sanford studied a discontinuous step function at the base of his model that would serve as an analogue computer to the analytical solution. In his now-famous model studies he reproduced the lower boundary condition by means of a movable hydraulic piston placed at the bottom and in the center of an aquarium filled with sand. Activation of this lower piston in an upward direction produces a series of faults that start out as vertical faults and flatten toward the surface to become first high-angle reverse faults and finally thrust faults near the sand-air interface. Behind these curved reverse faults a series of normal faults develop as a consequence of the displacements that occur along the reverse breaks (Fig. 10). It should be noted that when fault 1 in Figure 10 formed, the piston was not yet fully displaced. These experiments are very reproduceable, and the sequence of events is as follows: a fault takes off from the corner of the piston as a high-angle fault, begins to curve, then dies out; a second fault forms near the vertical portion of the first fault and continues higher into the section with the same pattern. In the experiment illustrated in Figure 10, fault 3 finally broke through to the surface, and as it was forming, fault 6 (a normal fault) formed behind the sweep of curved reverse faults 1 through 5. The precise number of faults that are formed varies, but the pattern of small faults dying out and then new faults forming as the displacement propagates upward is the common pattern. It must be remembered, however, that the horizontal parallel markers shown in Figure 10 do not constitute layering; they are merely original horizontal markers to keep track of the displacement field, and the sand in the box is a very homogeneous, isotropic material with no effects of layering. Therefore, any applicability that such experiments might have to reality will be restricted to rocks with those properties. For the foreland, this means that application is restricted to the Precambrian crystalline basement and must exclude the heterogeneous, anisotropic, inelastic layered sedimentary rocks above the basement.

The differences between the results shown in Figures 9 and 10 are striking and important. The main difference stems from the lower boundary condition. The condition that Hafner (1951) used (Fig. 9) is one in which the load differential is distributed over a broad region in the form of a sinusoid. This is in contrast to the lower boundary condition used by Sanford (1959). In Sanford's experiments, all of the differential displacement is distributed over a small region (the discontinuous step at the base of the block in Fig. 10). It can be seen that Hafner's lower boundary condition produces shear fractures throughout a broad region, and if activated, these fractures produce a series of rotated blocks across the entire area. However, Sanford's solution suggests that faults would be formed only at the edges of a plateau uplift. His solution should, then, best fit regions of plateau uplifts that are fault-bounded, such as the Beartooth Mountains (Foose and others, 1961). Indeed, this solution shows a remarkably good fit to the deformation along the front of the Beartooth Mountains, where drilling has established that a number of reverse faults, some of which are low angle, produce repeated sections of rock. Back in the Beartooth Mountains, where sedimentary rocks are in contact with Precambrian crystalline basement, the major faults are normal faults. This is precisely what would be expected if the basement in the Beartooth Mountains was being deformed by a system similar to that modeled by Sanford. As will be discussed below, faults that leave the basement at a low angle tend to propagate up through the sedimentary veneer as low-angle reverse faults. Therefore, faults 2 and 3 in Figure 10 would produce repeated sections in the sedimentary veneer, and faults 4 and 5 would break through and allow a plateau uplift of the crystalline basement. Such a movement plan does not result in the mechanical difficulties illustrated for the Beartooth Mountains in Figure 6 in which the mechanism of overthrusting or underthrusting is called upon. A slightly different problem, but still requiring differential vertical movements, is presented by Couples and Stearns (this volume) and fits the Beartooth deformation even better. Nevertheless, the work of Sanford (1959) remains a good model for this type of uplift.

Figures 9 and 10 represent two theoretical models for the types of faults that would be produced in thick brittle materials due to differential vertical loads deep within the crust. As valuable as they are for helping to understand certain regions, they represent but two loading conditions. Many other ways of loading the lower boundary can easily be imagined for a region as vast as the Rocky Mountains foreland. Despite this fact the models of Hafner and Sanford published during the 1950s remained until recently the only theoretical models with which to work. Couples (1977) introduced solutions to several different boundary-value problems that may be applicable in regions where the conditions of Hafner's or Sanford's models do not fit the observed geology. Some of the practical applications of these new models are presented by Couples and Stearns (this volume). Two extremely important implications come out of the new models. As is pointed out in detail elsewhere in this volume (Couples and Stearns), rotations of large blocks such as the Wind River Mountains in a direction opposite the motion on curved reverse faults no longer present a paradox. A slight change in the boundary conditions produces, in near proximity to each other, reverse faults and normal faults that can produce the previously difficult-to-explain geometries such as the Wind River Mountains and the Owl Creek Mountains (Couples and Stearns, this volume). The second important feature to come out of the new models is that Couples (1977, and this volume) demonstrates that horizontal end loads on a block, when superimposed on deep-seated differential vertical loads, alter the predicted fault pattern in detail but not in character. That is, the superposition of a horizontal load does not produce exclusively low-dipping overthrust-type faults. The dominant movements from such superimposed loads can still be vertical. The applicability of these new solutions clearly demonstrate a need for more boundary-value solutions with differing, but realistic, boundary loads.

The Uinta Mountains present a perplexing geometry that is relatively unusual in the Rocky Mountains foreland. The Uinta Mountains are flanked on both sides by large, curved reverse faults and seem to have been produced by a "mushroomlike" uplift. It is difficult to conceive of such a configuration resulting from a single loading condition. However, sandbox models such as those run by Sanford (1959) with slightly different loading conditions show that similar geometries are not incompatible with differential vertical movements. Sandbox experiments were run in which the rigid piston that produces step displacements was replaced by a partially inflated weather balloon. This partially inflated balloon, when covered with sand, forms an initial boundary that is somewhat elliptical in shape (Fig. 11a). With the sand covering the balloon to the top of the sandbox, continued inflation of the balloon produces a loading condition (Fig. 11b) that is significantly different from those used by Hafner (1951), Sanford (1959), or Couples (1977, and this volume). The overall geometry of the "faults" so produ~~ced is shown~~ in Figure 12 and is remarkably similar to that observed in the Uinta Mountains. The geometry includes a series of curved reverse faults on either side of the uplift and a large extension zone in the middle. ~~Although this similarity to the geometry~~ of the Uinta Mountains does not prove that they formed this way, it does demonstrate that their geometry is consistent with differential vertical movement in the total absence of horizontal motions.

The Colorado Front Range north of Denver, like the Uinta Mountains, present a complicated geometric form whose origin has long been argued. This range in all probability represents still a different loading condition that to date has not been examined in either a model or theory. However, Matthews (1976) and Matthews and Work (this volume) clearly show that differential vertical movement of discrete rigid basement blocks is the only system that is compatible with all of the geologic observations. Prucha and others (1965) showed that vertical uplift was compatible with the observations around Milner Mountain near Fort Collins, Colorado. Matthews and Work (this volume) have extended the principle in a rational fashion from north of the Wyoming state line to Denver. They clearly show along this continuous mountain front that there are three distinct styles that operate in adjacent areas. The styles range from curved reverse faulting (Denver) to gentle block motions in the north. None of these distinctive styles, however, is incompatible with differential vertical motions of rigid blocks within the basement. Palmquist (this volume) likewise shows that geologic observations made along the eastern front and southern part of the Big Horn Mountains are best reconciled by differential

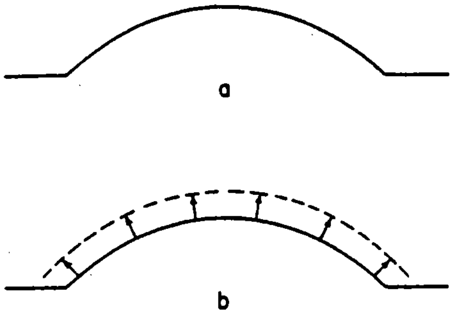

Figure 11. Illustration of the loading condition produced in homogeneous sand by starting with a partially inflated balloon (a) and further inflating it (b).

vertical block motions in the basement. He further points out that many structures that appear to be compressive in nature are secondary features formed by primary movements along high-angle faults.

It is concluded, therefore, that although large-scale basement shortening by underthrusting or overthrusting makes rationalization of the sedimentary veneer an easier task in cross section, total motions in the basement (Fig. 6) as well as block terminations (Fig. 7) make its acceptance as a unifying theory unappealing. However, the application of models for differential vertical uplift (Hafner, 1951; Sanford, 1959; Couples, 1977, and this volume) to specific mountain ranges produces a relatively good fit between prediction and actuality. Such theories have been applied to the northern Bighorn Basin (Stearns, 1975), the Beartooth Mountains, the Wind River Mountains, and the Owl Creek Mountains (Couples and Stearns, this volume) in a direct sense. Other regions such as the Front Range and the Big Horn Mountains as well as small features in the Beartooth Mountains and Seminoe Mountains are best explained by this style. In other cases, such as the Uinta Mountains, it has been shown that the total geometry is compatible with differential vertical motion (Fig. 12). In summary, then, it seems that most direct information concerning the real structures that involve basement material supports differential vertical motion in the upper part of the basement as the major component of the displacement field. Furthermore, these motions are accomplished by rigid-body rotations in the brittle basement.

Figure 12. Photograph of faults produced in a sandbox by inflating a balloon (lower center) beneath the sand.

BEHAVIOR OF LAYERED ROCKS

The make-up of the stratigraphic section influences the final fold geometry; however, our knowledge of forced folding is too meager to completely specify the details of that geometry at this time. That the final shape is at least partially controlled by the stratigraphy is an inescapable fact, and even now certain characteristics of the sedimentary section that do play a role in fold shape can be specified. Perhaps the most important factor is whether the folded strata are welded to the forcing member. The largest unfaulted folds occur where the layers above the forcing member are the freest to slip independently of the forcing member. A second factor that greatly affects the ultimate shape of the fold is the presence or absence of some controlling stratigraphic package that behaves in a relatively rigid fashion—that is, some stratigraphic unit that is thick enough to control the shape of the fold, but under the conditions of deformation is unable to thin or attenuate. If the sedimentary section contains a series of units that are unable to thin, even though other parts of the section are capable of thinning, it is comparable to placing a strut or reinforcing member in building materials. The behavior of the rigid unit then controls the shape of the fold.

There are at least three different general classes of sedimentary sections that will be considered here. First is a nonwelded section that contains a stiff or nonthinning stratigraphic unit that controls the shape of the fold. The second generalized section contains a welded, stiff, nonthinning controlling member. The third class of section is welded to the forcing member but is ductile and capable of thinning during the folding process. Between the first and third class is an almost continuous spectrum of behavior, and sharp division lines between the classes are nonexistent. However, there is enough difference in the behavior to speak about typical sections of each class to provide a standard of comparison. These three general classes are represented in various parts of the Rocky Mountains foreland.

Nonwelded, Nonthinning Sections

The first class of section exists throughout most of Wyoming, except in the extreme southern parts. The ~~Precambrian crystalline basement~~ which is the forcing member is immediately overlain by 275 to 400 m (900 to 1,300 ft) of Cambrian section that is dominantly shale. The shale behaves in bulk as a ductile material and allows nonwelded offset of the overlying layers in the manner illustrated in Figure 3b. From a structural standpoint the rest of the Paleozoic section behaves more or less as a single unit. The Ordovician, Devonian, and Mississippian rocks are almost entirely carbonates. The lower part of this middle Paleozoic section is composed of thick, bedded dolomites and limestones. The Pennsylvanian Amsden is a shaley unit, but too thin (less than 65 m) to have much control. This shale is overlain by a sandstone (Tensleep Formation) and Permian carbonates. The entire unit in the northern part of the Rocky Mountains foreland serves as a nonthinning strut and is about 600 m (2,000 ft) thick. This strut in turn is overlain by a series of Mesozoic clastic rocks that behave in a much different manner than the Paleozoic carbonates, but whose shape is more or less controlled by the behavior of the carbonate strut (Weinberg, this volume).

The behavior of this carbonate strut is best seen by observing its shape in a mature, well-developed forced fold. Perhaps the best exposure of such a fold both laterally and vertically occurs at Rattlesnake Mountain west of Cody, Wyoming. The overall structure at Rattlesnake Mountain (discussed by Stearns, 1971) is shown in cross section in Figure 5. Above the Cambrian and below the Triassic rocks, faulting plays only a minor role in the deformation and is restricted to the lower part of the post-Cambrian sedimentary section. Upward from the middle of the Paleozoic section, significant faulting is totally absent. To help clarify the discussion, certain blocks have been numbered 1 through 5 as indicated in Figure 5. These numbers refer only to the geometry of the post-Cambrian–pre-Triassic rocks. Block 1 is the gentle flank of the structure, and its dip conforms to the rotation of the upper basement surface. There is a reversal of a few degrees between blocks 1 and 2, so that block 2 dips as much as 15° in a direction opposite to that of block 1. Block 3 is everywhere steep; in most sections, its dips are nearly vertical, and it is connected to block 2 by a sharp hinge zone. Block 4 dips about 45° in the same direction as does block 2. The nature of the lowest block (5) on Rattlesnake Mountain is completely conjectural, but corresponding blocks are well exposed in several similar drape folds in the northwest Big Horn Mountains. These block designations apply only to this specific well-developed structure, but such designations will be useful in talking about deviations from the well-developed fold.

It can been seen in Figure 5 that the large basement fault with approximately 2,300 m (7,000 ft) of throw dies out upward quickly in the sedimentary section. The localized displacement along the fault in the basement is accommodated by folding in the sedimentary rocks as is schematically illustrated in Figure 1. The normal fault that marks the contact between blocks 1 and 2 in Figure 5 displaces layers higher in the section than most of the other subsidiary faults in the folded sedimentary rocks. In general as uplift continues, displacement by folding must reach a limit where folding can no longer keep pace with basement faulting. The layers would then fault through, probably along the normal fault shown between blocks 1 and 2. Examination of analogous, but slightly larger, structures in the nearby Beartooth Mountains leads to the suspicion that the sedimentary veneer on Rattlesnake Mountain has just about reached this point of separation. In the Beartooth Mountains, faults with 3,000 m (10,000 ft) of throw in the basement also cut the folds in the sedimentary rocks.

There are three important aspects of this geometry that should be emphasized. The first is that the hinges between adjoining blocks are fixed early in the deformation and remain hinge lines as the fold develops. That is, the hinge does not migrate through the beds during the deformation. The field evidence for this stems from the fact that the hinge regions are shattered by fracturing, and the segments between hinges are not only unshattered but, in general, they are linear noncurved segments (see Stearns, 1971). The second fact of nature that must be contended with is that there is no appreciable thinning within the carbonate strut across the fold (Stearns, 1971; Stearns and Stearns, this volume). These two observational facts, when combined, necessitate decoupling of the carbonate strut at least near the base of the section. Evidence for such decoupling is found at Rattlesnake Mountain (Stearns, 1971); it has occurred in both of the ways illustrated in Figure 3. The Cambrian shales behaved in a ductile fashion and responded quite differently from the overlying carbonate section, especially in the region between the basement and block 4 (see Fig. 5). In this region the Cambrian shales contain numerous large internal structures that are not present in the overlying sedimentary veneer, and there is an overall angular disconformity between Cambrian beds and the strata above. This type of behavior results in decoupling like that shown in Figure 3b. Discrete displacement across a single bedding plane (Fig. 3a) is found at the top of the first dolomite layer in the carbonate section. Such slip occurring between dolomite layers is understandable in light of experimental work by Logan and others (1972) that demonstrated that a brittle material sliding on a brittle material (for example, dolomite) has a lower coefficient of sliding friction than that for brittle materials sliding on ductile ones. There may be other detachments within the Paleozoic carbonate section that contribute to the lateral transport into the fold area, but as of now they remain unidentified. The movement path during the fold history of the Paleozoic carbonate package is not intuitively obvious. Detailed work on this kinematic pattern is fully discussed by Weinberg (this volume). His analysis, based on the model just presented, studies displacement into the fold of the carbonates as a function of vertical displacement and rotation of the basement block.

The sequence of development of the blocks (Stearns, 1971) empirically is determined from observing folds in the foreland at various stages of basement-fault displacement. Block 3 rotates to a near-vertical position before blocks 4 or 5 are activated (Fig. 13). In Figure 5 notice that the Ordovician Bighorn Dolomite (base of the Paleozoic strut) is nearly in contact with the basement block because the entire Cambrian section has flowed into what otherwise would have been a void created by the faulting. Once the hinge between blocks 3 and 4 has been laterally transported into this position, it can no longer move horizontally, and the development of block 4 is necessitated. Incipient formation of such a block 4 is observed in the northern Big Horn Mountains, and in these cases block 3 has already migrated to a vertical position. The existence of block 4 on all large drape folds is more difficult to prove than blocks 1, 2, and 3 because of depth of erosion required

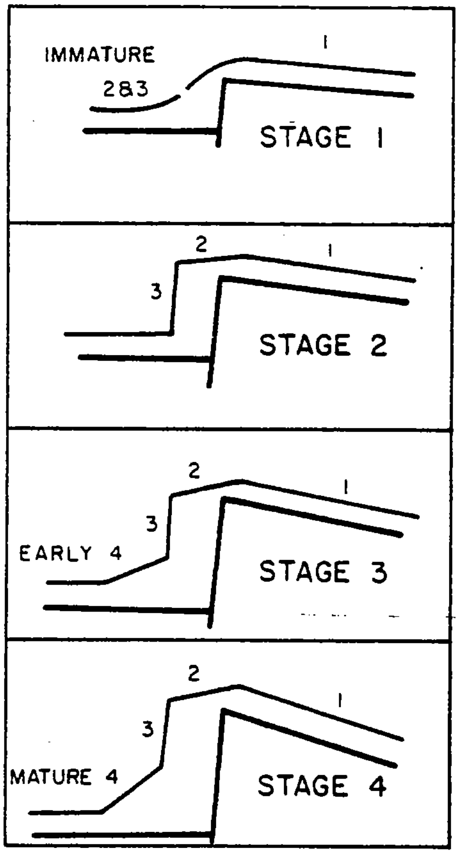

Figure 13. Postulated order of block development in the Paleozoic carbonates during the growth of a forced fold in the northern Rocky Mountains foreland. Numbers refer to blocks defined in the text.

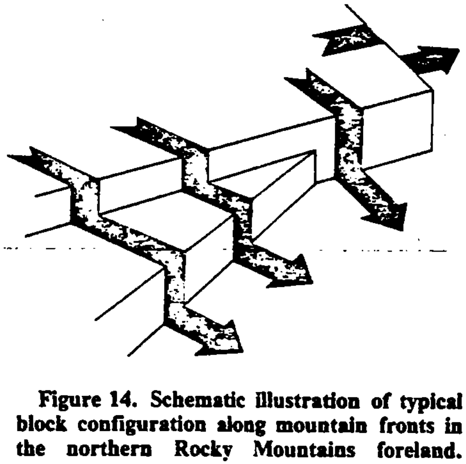

Figure 14. Schematic illustration of typical block configuration along mountain fronts in the northern Rocky Mountains foreland. Arrows represent folded sedimentary layers.

to expose block 4. A block 4 is well-developed, however, on other deeply dissected structures, but the universal presence of block 4 in such situations is still a matter of conjecture.

To this point, the discussion has been restricted to cross-sectional geometries near the centers of single rotated blocks. However, one of the characteristics of forced folding in the Rocky Mountains foreland is that the folds do not form in parallel fold trains. The shapes, trends, and sizes of the forcing member, which in the Rocky Mountains foreland is Precambrian crystalline basement, determine the ultimate geometry of the folds in the layered rocks. The basement blocks and, therefore, the folds terminate abruptly along strike. This type of termination is illustrated in Figure 7e. The interior angles at block corners usually are between 70° and 120°. If the block is rotated, the folding dies out along the terminating fault in the downdip direction (Fig. 7e). Therefore, unlike free folds, some of which tend to die out in long plunges along strike, forced folds die out by turning an abrupt corner and losing throw in a direction at high angles to the average fold strike. Furthermore, when several basement blocks with different strikes and different rotations adjoin one another, the resulting fold geometry can become very complex and unpredictable (Fig. 14). Although Figure 14 is idealized, it is taken from actual cases and is representative of the types of complex geometries that can result from multiple block rotations in the same area. Even though on the state geological maps the mountain fronts in northern Wyoming appear to be straight, they are in fact composed of multiple blocks that abruptly change strike along the front. That is, the front is rarely formed by a single fault the length of the mountain system, but rather by a complex of rotated blocks. This situation gives rise to abrupt changes in the strike of the frontal fold. This is particularly well illustrated along the western front of the Big Horn Mountains between Lovell and Greybull, Wyoming, along the steep western front of the Gros Ventre Mountains, along the steep south flank of the Seminoe Mountains, along the south flank of the San Juan Mountains, and all along the east side of the Front Range. That the Paleozoic rocks are able to conform to such complicated forced shapes without thinning or faulting appreciably is a poorly understood fact. However, lack of understanding should not be confused with the fact that the continuous folds do exist. Such geometries are discussed in detail for an area in the northern Big Horn Mountains by Stearns and Stearns (this volume). They discuss, primarily from field observations, the facts of these geometries and rule out certain obvious explanations. Although their purpose is primarily to define the problem, they conclude that whatever the total mechanisms are for achieving these complicated shapes, bedding-plane detachments and movements in three directions are necessary.

Perhaps the most perplexing, and difficult to understand, feature of the forced folds in the Rocky Mountains foreland is the behavior of the stiff carbonate strut at the termination or corners of the forcing block. The features of such corner areas are discussed by Stearns and Stearns (this volume). That the layered carbonates can conform to the shape of the forcing member without thinning, faulting, or the creation of subsidiary folds is an observational fact. This leads to the inevitable conclusion that the carbonate strut must be detached from the underlying materials and free to translate in virtually any direction required by the folding. Although the forcing member may be more highly broken at such corners, as will be discussed below, layered carbonates accomplish their new shape with a smoothness and continuity that is difficult to accept. Such corners are, however, observable in folds too numerous to list within northern Wyoming and in such sufficient numbers that the observational fact must be accepted as part of reality. That the carbonate strut must detach and slide into the fold in many directions is further attested to by the work of Vaughn (1976). In her work at Casper Mountain she studied a series of corner configurations within the more-ductile Mesozoic part of the section. She found that at the corners, these more-ductile rocks show a considerable amount of local thickening and thinning in order to accomplish the fold process. Such thickness changes require that a great deal of material must either move into or away from the corner area. If, on the other hand, the geometry is accomplished with no thinning or rupture, as in the carbonate strut, it must mean that differential motions in many directions occur along bedding-plane detachments. The fact that these movement patterns cannot be reconciled into a rational framework at this point should not be confused with the evidence for their existence.

The behavior and shape of the Mesozoic rocks during forced folding in the northern Rocky Mountains foreland are not as well defined nor as well studied as for the Paleozoic section. The primary reason for this lack of observational control in the Mesozoic rocks is erosion. Most of the mountain ranges, from which the Paleozoic information is derived, are eroded either completely through the Mesozoic strata or at least to the lower sequences. Furthermore, even on the low mountain flanks where Mesozoic rocks are preserved, they tend to develop soil cover and vegetation much more rapidly than do the Paleozoic carbonates. As a consequence there simply is not as much exposure of Mesozoic rocks on these forced folds compared to the exposure of Paleozoic rocks. This is particularly true in the critical hinge areas where outcrop is sparse in the Paleozoic part but nearly absent in the Mesozoic part of the section. However, certain generalities at least can be made. The most striking observation is that within the Mesozoic section the distinct block shape of the deformed Paleozoic strata gives way to a more uniform, continuous fold that is best represented by arcs of large circles as opposed to straight linear segments (see Weinberg, this volume). This may indicate that the folded Paleozoic rocks serve as a loading condition for a new forced fold in the Mesozoic rocks. Exactly where within the Mesozoic strata this transition occurs is not known. The smoother folding is usually in existence by the middle of the Mesozoic section, and quite frequently the Triassic strata (Chugwater) still show good conformity to the blocks of Paleozoic rocks. However, even in the Chugwater where there is some hinge exposure, the flexing is not as sharp as in the Paleozoic rocks. Therefore, it seems that the transition from sharp, linear segmented folds to smooth rounded folds occurs gradually. The material properties of the sandstones and shales that make up the Mesozoic section are such that thickness changes by ductile flow are more likely in Mesozoic than in Paleozoic strata. That this generality is true is substantiated on many folds where thinning and thickening, particularly in the shale units, are noted. However, the order or pattern, if it exists, has not yet been delineated. Certainly, the best understanding of the overall Mesozoic section results from the work of Weinberg (this volume) in which he considers the kinematics demanded of the Mesozoic section by the folding of the Paleozoic rocks. His studies show that under very reasonable conditions and at certain stages of the folding, an excess of Mesozoic rock material may be expected. The manifestations of such a movement pattern are certainly recorded in many areas. In drilling it is not uncommon to find many more repeated sections of Mesozoic rocks on the flanks of forced folds than of Paleozoic rocks. In addition, Weinberg (this volume) describes a class of secondary folds (drape subsidiary folds) that are frequently present in the Mesozoic section on forced folds, but are absent in the Paleozoic rocks. The precise mechanisms within the Mesozoic section, nonetheless, remain an unsolved problem. Particularly important for future studies is the determination as to the relative role of the two types of bedding-parallel offset illustrated in Figure 3. It is not known at this time whether there are favored slip horizons that produce displacement such as in Figure 3a or whether thick sequences behave as shown in Figure 3b with no sharp bedding discontinuities.

Welded, Nonthinning Sections

During Paleozoic time the area of south-central Wyoming was intermittently high relative to the shelf region of northern Wyoming. The most important stratigraphic change (from a structural point of view) that resulted is that the thick Cambrian shale section, present in northern Wyoming, was completely replaced by a thin transgressive sandstone of Late Cambrian age. In addition, the carbonate strut that is well defined in northern Wyoming was reduced in thickness so that it consists essentially of just the Mississippian Madison Limestone. The Pennsylvanian sandstones that were present in northern Wyoming are still well developed in southern Wyoming, but the Permian section lost many of the limestone units, which were replaced by red beds and limey siltstones. The net result is that not only has the strut in the package been reduced in thickness, but by the disappearance of the Cambrian shale section, the layered rocks have become more welded to the basement than in northern Wyoming.

Although this region has not been studied as thoroughly as the areas farther north and south, even a reconnaissance trip through the region indicates that forced folding is still a dominant structural style. Drape folds in the Paleozoic rocks can be observed at Casper Mountain and throughout all of the mountain systems that flank the Hanna Basin. The main differences seem to be that although block 1 and block 3 are well developed, the hinges between blocks 1 and 3 are not as distinct and as sharp as they are farther north. That is to say there is more broad arching between blocks 1 and 3 in southern Wyoming structures than in those farther north. Furthermore, there is definitely a tendency for the folds to fault through at lesser displacements than there was farther north. In the area of Rattlesnake Mountain, the layered rocks are able to fold without rupturing over basement faults with 2,500 m (8,000 ft) of throw. More work needs to be done in the south-central region of the Wyoming province to pin the limiting displacement down more precisely. The displacements range from about 1,250 to 1,500 m (4,000 to 5,000 ft) before separation occurs and perhaps in some cases as little as 1,000 m (3,000 ft). Another difference that seems to occur is that the basement frontal fault system contains more small splinter faults than occur in the northern part of the province where detachment or offset of the layered rocks is more easily accomplished. This splintering probably forms in order to accommodate the space requirements near the interface between basement and layered rocks. Figure 5 shows a triangular region formed between the base of the Paleozoic carbonates, the frontal fault in the basement, and the downthrown basement surface. Where thick shale sections exist, this triangle is filled by ductile flow of the shales themselves. In southern Wyoming where the ductile shales are absent, the basement seems to fragment into small frontal splinters that partially satisfy the space filling of this triangle. Vaughn (1976) reported such behavior along the Casper Mountain front (Fig. 15), and it can also be observed in the deep canyons in the Seminoe Mountains. This development of multiple splinters along the main fault front has also been reproduced experimentally (Fig. 16). Beneath the folded, layered material and in front of the main fault there are a series of small curved reverse faults in the brittle material that essentially accommodate the space requirements between the faulted, brittle layers and the folded, more-ductile layers.

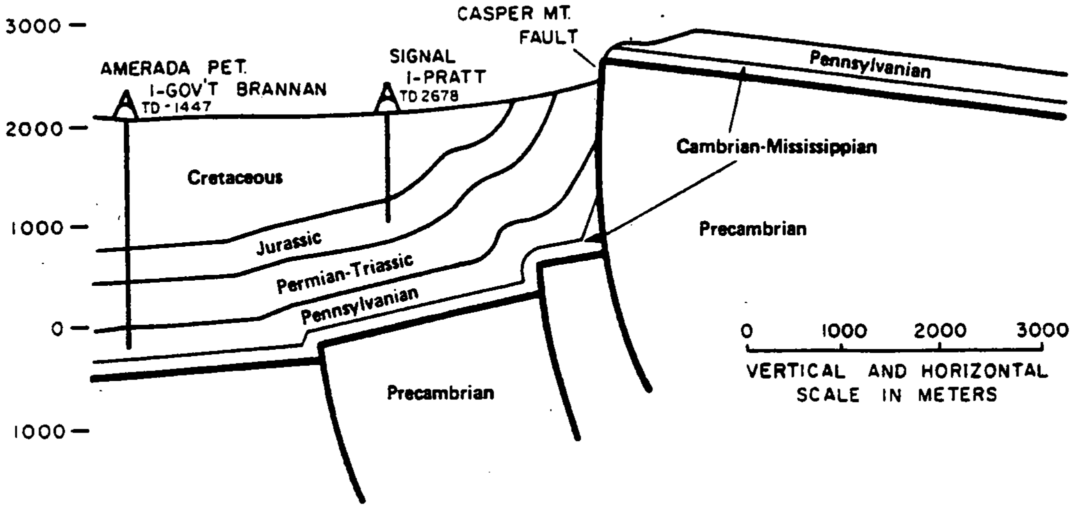

Figure 15. Cross section of Casper Mountain (after Vaughn, 1976).

Nowhere in southern Wyoming can a block 4 be observed along the drape-fold fronts. This could be simply a coincidence of erosional depth. However, there are arguments indicating that block 4 may not form under these circumstances. The kinematic studies of Weinberg (this volume) show that block 4 does not begin to form until there is about 1,500 m (5,000 ft) of displacement on the fold. Should rupture of the folded layers by faulting occur at this point, there would be no need for block 4 to form in the fold. Therefore, it is reasonable to speculate that in the regions where the layered rocks are more welded to the basement and faulting of the sedimentary section occurs at lesser displacements, a block 4 may never develop.

Welded, Ductile Sections

The third type of section to be considered is that of a welded, but ductile structural unit lying immediately above the forcing member. Such a situation is well exposed in the Colorado National Monument on the northeast flank of the Uncompahgre uplift. Here, Precambrian crystalline basement blocks have been differentially uplifted; this forced Mesozoic rocks, primarily eolian sandstones, to be folded over the blocks.

The folds formed during Laramide deformation and the unconformity between the Precambrian and the overlying Triassic sedimentary rocks reflect Ancestral Rocky Mountain movements (Pennsylvanian and Permian). The Triassic Chinle Formation (20 to 25 m thick), which lies directly on the Precambrian basement, is composed of the typical red continental sandstones, siltstone, and shale common to the Colorado Plateau. Overlying the Chinle is the Upper Triassic Wingate Formation; a cross-bedded eolian sandstone approximately 100 m thick. The Lower Jurassic Kayenta Formation is a cross-bedded, highly lenticular, medium- to coarse-grained sandstone with a thickness of about 25 m. The overlying Jurassic Entrada Formation is similar to the Wingate Formation in that it is a massive, cross-bedded sandstone. Where it is flat-lying, the Entrada Formation is about 40 m thick. All of these rocks were once overlain by the Jurassic Summerville and Morrison Formations and a thick section of Cretaceous rocks. Because rocks

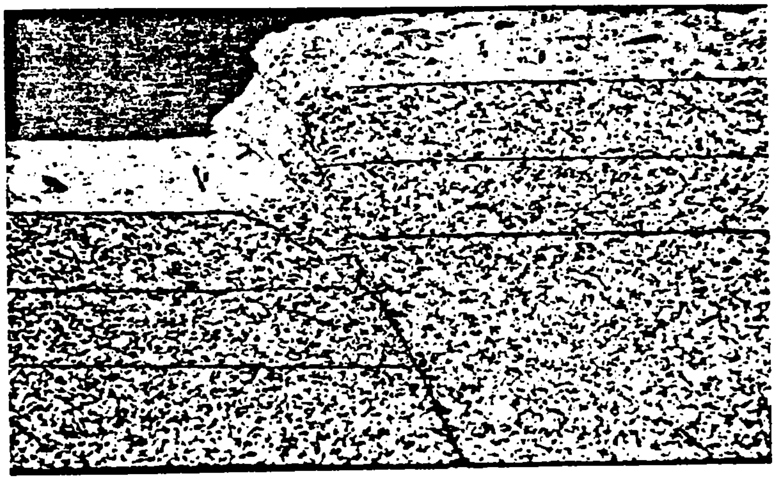

Figure 16. Thin section of experimentally deformed sequence of sandstone and limestone. The lowest sandstone member has been displaced along a 60°-dipping precut fault; this produced the deformation in the overlying material. Under the conditions of the experiment, the sandstone is brittle relative to the limestone (from Friedman and others, 1976).

younger than the Entrada Formation are not preserved within the drape folds, they will not be considered here.

The folds form over a series of steep faults in the Precambrian basement rocks (northeast flank of the Uncompahgre uplift). The zone of faulting and flexing is about 1.6 km wide with the maximum fault throws on the order of 350 m (1,200 ft). On the downthrown side of the zone, older beds are covered by alluvium from the Colorado River. On the upthrown side, the beds are flat-lying and form the Uncompahgre Plateau.

In the Colorado National Monument, at least within the area of exposure, the rock column consists of only two mechanical units: the Precambrian crystalline basement and the overlying clastic rocks. This is in contrast to Rattlesnake Mountain where in excess of 300 m of ductile shale separates the basement from the folded layered rocks. The basement faults die out upward within the first 30 m of the Triassic sedimentary rocks.

Several canyons cut through the sedimentary rocks into the basement and trend normal to faults so that they provide excellent exposures in the vertical plane. Most of the data for the controlled cross section in Figure 17 are subject to direct observation. This cross section at first glance is similar to those across Rattlesnake Mountain: the hinges between the blocks are unfaulted, and the blocks are well defined. The principal difference between the folds in the two areas is the lack of thinning at Rattlesnake Mountain and the extreme thinning at the Uncompahgre uplift. This means that there is no need for detachment at the Uncompahgre uplift because volume remains constant owing to thinning across the fold. The Wingate sandstone has, for example, attenuated from 110 m in block 1 to 59 m in the upper part of block 3. There are other canyons along this front where the Wingate is thinned to less than 30 m. This thinning is accomplished by cataclastic flow (Stearns, 1969). Individual beds within the Wingate Formation are capable of large flow by cataclasis. A bed of 2-m thickness can be reduced to less than a few centimetres by flow that is accomplished by both internal fracturing of the grains and macrofracturing within the formation. This thinning attests to the very macroscopically ductile behavior of the sandstone units in this area.

It is concluded that if as a whole the layered section immediately above the forcing member is very ductile, the layers thin, and there is no need for detachment. This, then, represents the same mechanical system as is represented in the Northern Rocky Mountains, but the mechanism of fold formation differs because the material response of the overlying rocks is different.

Another example of welded, ductile sections occurs along the southeastern flank of the Hanna Basin, in the vicinity of the Freezeout Mountains. Here the basement is overlain by a very thin section of Mississippian limestone that in turn is overlain by thick clastic sequences of the Casper Formation (Pennsylvanian). Even this section is capable of involvement in forced folds with up to at least 1,000 m (3,000 ft) of displacement without rupturing, as can be seen along the fronts of the Freezeout Mountains. However, the Casper Formation along these folds is thinned by cataclastic flow. Whether the thinning completely accommodates the necessary geometry or whether a combination of detachment plus thinning is responsible is not known. Detailed measurements along these mountain fronts need to be made in order to answer this question more precisely.

An area that is transitional between welded, nonthinning and welded, ductile sections is along the Front Range of Colorado. Here the entire sub-Pennsylvanian carbonate section was removed by erosion following uplift of the Ancestral Rocky Mountains. The Fountain Formation (Pennsylvanian) lies immediately on top of Precambrian granite. That the lower part of the stratigraphic section is more faulted in this area than in northern Wyoming is demonstrated by Matthews and Work (this volume). However, even this section is capable of considerable drape folding over the uplifted basement blocks, as is discussed by Matthews and Work. The most remarkable aspect of these sections is that they can fold as much as they do without faulting. One of the better-exposed folds of this type occurs at Elk Mountain west of Laramie, Wyoming (McClurg and Matthews, this volume). Elk Mountain has a well-developed block 1. There is sufficient relief along its steep front to show that forced folding in the layered rocks is continuous for at least 1,000 m (3,000 ft) over the basement fault.

Behavior at the Corners of Basement Blocks

As discussed by Stearns and Weinberg (1975) and shown experimentally by Friedman and others (1976), the sharp corners of the basement blocks are frequently

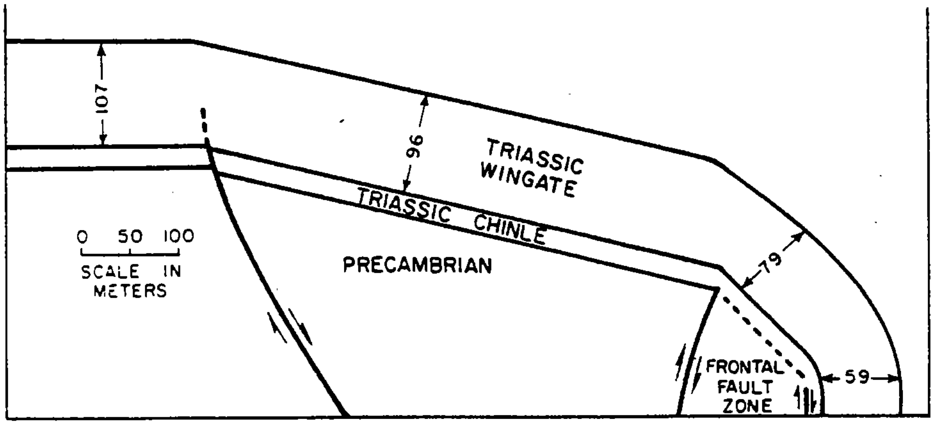

Figure 17. Controlled cross section along North Entrance Canyon in the Uncompahgre uplift showing the thinning in the Wingate Formation as it passes through a forced fold over rigid basement blocks.

sights of anomalous behavior in the forcing member. As the sedimentary rocks drape around the sharp corners, stress concentrations are created in the brittle basement. As a result, large-scale cataclastic flow can develop in these corner areas. Pieces of the sharp brittle corners are literally torn off by the folding of the overlying continuous layers, and pseudofolding of the basement results. In these regions, instead of a uniformly dipping, upper basement surface, large blocks of granite are crushed and rotated relative to one another so that a smooth, rounded fold can develop in the layered rocks. The scale at which this pseudofolding of the forcing member occurs is trivial with respect to the scale of the larger feature of which it is a part. This sort of behavior at corners should not be confused with the overall behavior of the basement block, which remains brittle and rigid.

There is another type of fold that results from block rotations but is not a forced fold. This fold results when blocks are rotated in the same general direction, but along different axes of rotation, as illustrated in Figure 18. This sort of fold results from an excess of material in the layered rocks where the two blocks join one another. As the blocks continue to rotate and the fold grows, the hinge area migrates through the beds. That is, this type of fold, unlike the drape fold, does not have fixed hinges in the Paleozoic strata. A particularly well-exposed example of this sort of folding is the Pat O'Hara structure that lies between the rotated Rattlesnake and Dead Indian blocks near Cody, Wyoming. The Rattlesnake Mountain block strikes northwest and is rotated toward the Bighorn Basin. It adjoins the Dead Indian Hill block, which is also rotated toward the Bighorn Basin, but which strikes more northward than the Rattlesnake Mountain block. Between the two blocks, the Pat O'Hara structure occurs. It terminates where the two blocks adjoin, and it broadens rapidly basinward. In such folds because the hinges do migrate through the beds, the Paleozoic rocks are completely shattered throughout the fold, not just at hinge lines.

FIRST MOVEMENTS OR ULTIMATE CAUSES

In the past few years a great deal has been learned about deep-crustal or upper-mantle movements that are the ultimate cause for surficial mountain terrains. We owe much of our current thinking on ultimate causes to solid-earth geophysicists, thermodynamicists, and oceanographers. However, most of the data that have led to a better understanding of the deeper Earth have been accumulated from the ocean or near continental edges. There is, perhaps, at least a tendency on the parts of some writers to make an unsubstantiated extrapolation or extension of these data to continental interiors. Ultimately, there may be a justification for

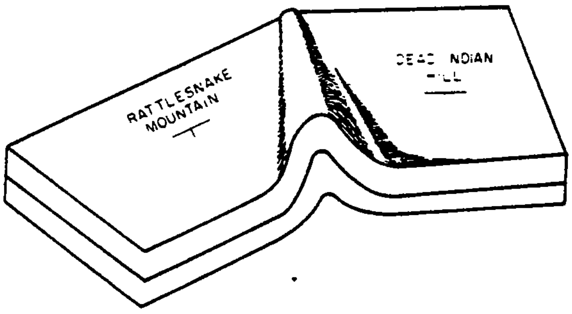

Figure 18. Sketch of the type of fold that can form when two basement blocks are rotated toward one another. This is not a forced fold.

such extrapolations. However, it seems that with the current state of knowledge, there is more speculation than there is substantiation when it comes to dealing with first causes for continental-interior movements. Wholesale extrapolations of proved continental-edge systems into the interior of continents, with no geophysical justification, may be unwarranted. Nonetheless, certain observations regarding the surficial structures can be made so that at least the problem can be specified if not solved. These specifications can at least place some restraints on an ultimate solution once the thermodynamics of continental interiors is more fully understood.

The first of these observations is that within the Wyoming province throughout Phanerozoic time and especially during Cretaceous and Tertiary time, differential vertical movements at the surface have dominated over horizontal movements. The very fact that there is a systematic development of deep intermountain basins surrounded by large uplifted mountains makes this conclusion unavoidable even though the whole continent may have been translated horizontally by plate motion. Furthermore, whatever the deep-seated motions are that produced the surficial motions, a fault *system* that arises from broad-scale uplift and downdropping seems to fit best with the observational facts. Although in detail the theory may be incorrect and the necessary assumptions may be geologically naive, solutions similar to those of Hafner (1951), Sanford (1959), and Couples (1977, and this volume) explain too many features of the region to be ignored. These features include an intermixture of fault types, rotations of large blocks, position of faults, and curvature of faults. Therefore, it would seen that whatever is postulated within the deeper portions of the Earth as a first cause, it must be able to produce broad-scale, absolute upward motions as well as broad-scale downward motions.

As argued earlier, localized horizontal motions as an explanation for the various orientations of mountain fronts seems implausible. However, that there is some deep-seated (lower-crust or upper-mantle), east-to-west transport of material would at least seem to be substantiated on the largest scale. By the end of Triassic time the upper part of the crust dipped gently westward throughout the Rocky Mountains foreland. However, by mid-Cretaceous time, conditions had drastically

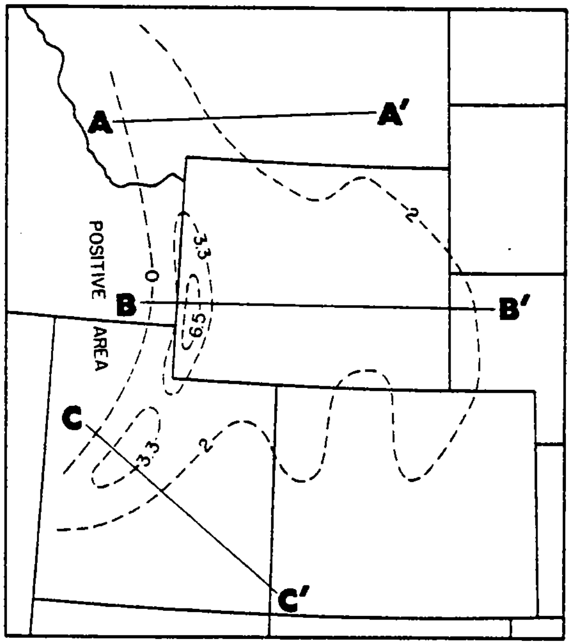

Figure 19. Isopachs (in kilometres) for Upper Cretaceous sedimentary rocks in the Rocky Mountains foreland (modified from Haun and Kent, 1965).

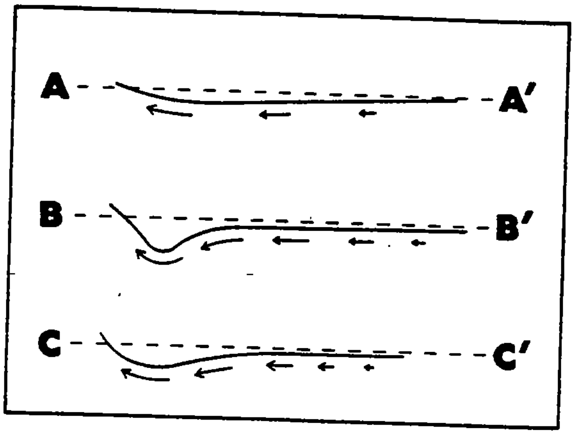

Figure 20. Cross sections in deep crust taken from data in Figure 19. Lines located in Figure 19. The arrow lengths are proportional to the amount of transfer required to produce the deviation from horizontal "dashed lines."

changed with the development of a positive area in the west and an asymmetrical trough immediately to the east (Fig. 19). Not only was the trough asymmetrical, but in it along its axis, lows of different depths were developed. The positive area changed strike considerably along trend. In order for this to happen in the shallow crust, there must have been material transferred from deep beneath the trough (near the Moho) into the newly created positive area. Certainly, along the positive area there are many instances of regenerated rock intruded into the shallow crust. Such transfer could have produced east-to-west transport in the lower crust or upper mantle. Furthermore, the amount of material withdrawn from the trough region would have been somewhat in proportion to the depth of the trough (Fig. 20). Because of the irregular nature of the trough, the net results would be differential lateral motion from north to south that died out to the east (Fig. 21).

The main justification for even considering differential lateral motions within the deep material comes from the broad-scale observations made by Sales (1968). The similarity he achieved in his barite-mud model when compared to the overall

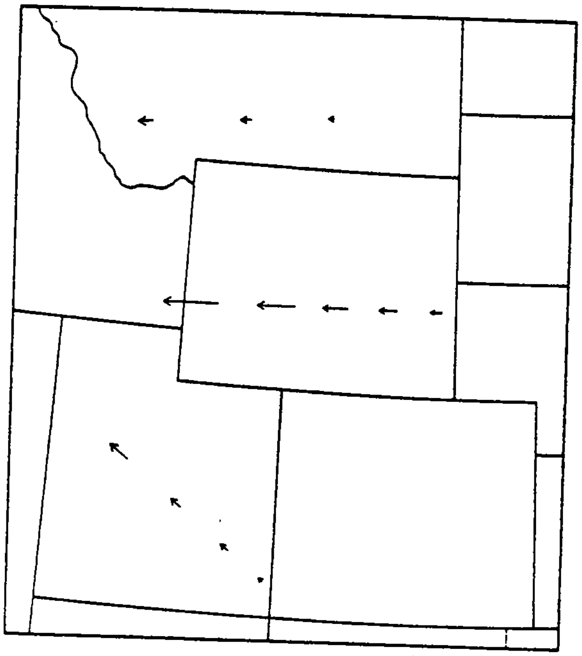

Figure 21. Schematic illustration of the relative lateral motions deep within the crust to produce the upper-crust configuration shown in Figure 19. The arrow positions and lengths are taken from Figure 20.

distribution of mountain systems and basins within the foreland is a remarkable geometric comparison. To produce a geometric similarity to any single mountain system or basin within such a modeling system could very well be ascribed to coincidence. However, in Sales's models, which are produced by a widespread mechanical couple in ductile material, there is geometric correspondence to virtually all of the major features in the state of Wyoming east of the thrust belt. Applying the uplifts and depressions that Sales produced in a very ductile material to the upper part of the brittle Precambrian basement may be mechanically naive. However, the upper surface of the Sales model could be considered to be in the lower crust or upper mantle where owing to pressure and temperature conditions, the rock materials can behave in a highly ductile fashion. As such it might serve as a model to the loading conditions that produce the discrete faults in the upper, brittle part of the basement. This, of course, is rank speculation, but the simultaneous creation of so many different geometries compared to what is actually seen in the field makes it an attractive speculation at least. It is also interesting to note that the widest, and best developed, part of the foreland (that is, most of Wyoming) occurs just to the east of the deepest part of the Cretaceous trough. Evidence for an eastward decrease in the amount of horizontal compression is presented in Couples and Stearns (this volume).

Even if there is some correspondence at depth (such as postulated by Sales, 1968) that is produced by differential lateral motions, it should be pointed out that such a system would need to be decoupled from the upper crust (both upper basement and layered sedimentary rocks). The justification for such a statement lies in the fact that lateral motions (that is, along wrench faults) play virtually no role in the displacement patterns in the upper basement or layered sedimentary rocks of the foreland. As was pointed out above, differential rotations of blocks can give a pattern similar to that which would be produced by lateral faulting (Fig. 7). However, examination in the field of mountain front after mountain front clearly demonstrates that there are no large-scale lateral motions in the surface rocks. Of all of the classical fault types, wrench faulting plays the least role in the formation of surface structures in the Rocky Mountains foreland. Nowhere in the surface rocks are there large-scale offsets that could be considered controlling features. Therefore, if lateral motions play a large role in the formation of the mountain structures in the Wyoming province, they must be deep within the crust and essentially decoupled from the upper-crustal materials. That is, their role can only be setting up broad-scale upwarps and downwarps in the ductile materials that in turn produce the lower loading condition for the upper, much more brittle materials.

CONCLUSIONS

There is an entire class of folds that can develop when loads are at high angles to planes of anisotropy within rock sections. These folds are forced folds. In most cases this anisotropy is sedimentary layering. Within this general class there are particular adjectives that apply to certain folds, such as drape folds or diapiric folds. Furthermore, in the case of drape folding, the kinematics and dynamics that determine the ultimate form depend upon many physical parameters such as rock type, depth of burial, degree of welding, and whether the rocks are in layer-parallel extension or compression.

The Wyoming province serves as an excellent example of some of the types of forced folding as demonstrated by field exposures over the entire province.

Virtually all mountain ranges within the Wyoming province exhibit some form of forced folding in the layered sedimentary rocks. In addition to field evidence for the existence of this type of structure, such folds have also been created experimentally. When layered rock materials in the laboratory are subjected to differential vertical movements of a homogeneous, brittle member from below (forcing member), many of the features seen in the field can be reproduced in the laboratory (Logan and others, this volume).

If first causes in the Rocky Mountains foreland are ever to be understood, more geophysical studies are needed. It is unlikely that the true causes at depth will be unraveled from scattered surface data alone. In addition, it may be misleading to make wholesale extrapolations from the thermodynamics of continental edges to continental interiors. Even if such extrapolations turn out to be justified, they are not more than lucky guesses at this time without geophysical studies to back them.

There are numerous ways in which layered rocks can be loaded at high angles to their planes of anisotropy, and more of these loading systems should be investigated. The smooth sinusoids of Hafner (1951), the sharp steps of Sanford (1959), and the sawtooth configuration of Couples (this volume) are but a few of the conditions that lead to faults that load the layered rocks, and further work is needed to delineate other possible loading conditions.

Bedding-plane detachments play a very major role, at least in the Wyoming province, in the resulting structures. Therefore, lateral motion of layered rocks during the folding process deserves considerably more attention than it has received in the past. Much data (see Stearns, 1975; Vaughn, 1976; Cook and Stearns, 1975; Weinberg, this volume; Stearns and Stearns, this volume) indicate that some of these lateral displacements may be large. Furthermore, in order to produce these continuous folds, lateral displacements must occur in three dimensions. Therefore, if understanding of this folding process is to be enhanced, the three-dimensional kinematics on a large scale must be investigated. From a geologic standpoint this would seem to be the most necessary area of new work. That is, cross sections of regions near the centers of the blocks are relatively well delineated in terms of the final configuration of the fold. However, the internal displacements that are required to produce such large-scale folding are but remotely understood, and the total displacement field required within large blocks with thousands of square metres of surface area has never been properly investigated.

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